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Journal of the

IRRIGATION AND DRAINAGE DIVISION

Proceedings of the American Society of Civil Engineers

AQUEDUCT CAPACITY UNDER AN OPTIMUM BENEFIT POLICY

By Warren A. Hall,[1] M. ASCE

SYNOPSIS

Aqueducts are often designed to serve a number of geographic districts located in sequence along the supply line. The beneficial returns (however they are to be defined) will not, in general, be the same from district to district and will be non proportional functions of the quantity of water to be delivered. If the available supply of water will be less than the maximum demand, there exists the problem of determining the "best" allocation of water to the various districts.

This question presents a very large number of alternatives, incapable of solution by direct comparison even with high speed digital computing machinery. In this paper a method of solving this problem using dynamic programming as an optimization device is presented. Because of the characteristics of dynamic programming, the individual allocations are obtained as a function of the total supply which might be made available at the head of the aqueduct. The total net beneficial return is also a function of the total supply. Thus, ex-

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cept for intangibles, the merits of increasing or decreasing the supply for this aqueduct as compared to other potential uses can be directly determined.

INTRODUCTION

The fundamental problem of water resource development is the question of determining the engineering works to be constructed, the location of these works, and the capacity limits to be imposed. The answers to this fundamental question depend upon the broad, dynamic, socio-economic situation as well as the particular physical and econometric parameters entering into the engineering analysis. In general, it may be said that the decision concerning location, kind and extent of engineering works to be constructed is intended to be such as to provide a net "beneficial return" (however "beneficial" may be defined) which is optimum.

There are many difficulties associated with optimal beneficial analysis, not the least of which is the complexity introduced by even a relatively small number of alternatives.[2] Even where the aqueduct location is rather narrowly determined by geographic factors, there remains the problem of determining what capacity is required as a function of position on the canal so as to maximize the overall return from the aqueduct. This maximization must include canal costs and net benefits derived from water deliveries. Thus, there are not only the alternatives concerning which geographic sub-districts shall be served, but also concerning the level of service.

By direct alternative analysis, such an optimization is virtually impossible, even with an army of high speed digital computers. A methodology for optimum analysis of canal capacity which reduces the problem to a simple computer solution and in some situations to relatively simple hand calculations will be derived.

In order that the method of analysis be emphasized, certain subsidiary problems of information are not treated. For example, it is presumed that information at a suitable level of accuracy is available concerning the net benefit to be obtained from water deliveries to any geographic sub-district as a function of the quantity delivered. It is also presumed that aqueduct cost information is known with a reasonable degree of accuracy for the representative reaches between geographic districts, again as a function of capacity required to deliver the water when and as required. These data are, of course, obtainable, whether presently existing or not, for today's situation. Some argument might be raised concerning future benefits and demands and the accuracy of such predictions.

Decisions may not be postponed indefinitely solely because of inability to provide precise information. For purposes of the present analysis it need only

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2 "The Dynamic Programming Approach to Water Resources Development," by W. A. Hall and N. Buras, Journal of Geophysical Research, Vol. 66, No. 2, February, 1961, pp. 517-520.

be required that the information available is at least as accurate as the information available for decision based on any other method of analysis.

OPTIMUM BENEFIT ANALYSIS

Dynamic programming[3] has been chosen as the optimizing procedure for optimum benefit analysis for aqueduct capacity determination. Dynamic programming is well suited to multi-stage decision processes for which an optimum policy is desired, and for which the benefits or costs or both, are not simple, well-behaved linear functions of the resource to be allocated. It is less well suited to problems involving allocation of more than one resource, although this is not impossible. Because water is the resource of major concern here, it will be presumed that all other resources necessary are available at a price, not necessarily constant.

Let $v_i(q_i)$ represent the net beneficial return to the i^{th} geographic district as a result of making available to that district a quantity of water q_i, exclusive of aqueduct costs incurred to bring water to the district. Let C represent total cost of the main aqueduct serving n such geographic districts. Let Q represent the maximum quantity of water that might be made available to these districts. Then the problem of optimization is to select the set of values q_i, $i = 1, 2, 3, \ldots n$, such as to maximize the sum of the returns less total aqueduct costs.

$$V = \max \sum_{i-1}^{n} \left[v_i(q_i) - C(q_1, q_2, q_3, \ldots q_n) \right] \ldots\ldots \quad (1)$$

subject to:

$$\sum_{i=1}^{n} q_i \leq Q$$

Direct solution of Eq. 1 is virtually impossible even for a small number of geographic districts because it is essentially trial and error in nature.

The order in which the districts are numbered is at the user's disposal. To eliminate problems which will otherwise exist, the districts will be numbered beginning with the district at the end of the aqueduct, sequentially in order, back to the head of the aqueduct.

The dynamic programming method proceeds by presuming for the moment that a problem exists only with respect to the last user on the aqueduct, numbered 1 in our system. A reach of aqueduct, also designated as reach number 1 carries the water from the next to last user's turnout (numbered 2) to the last user's headgate. This canal must have a capacity sufficient to deliver the quantity of water to be used by district 1.

Now presume that after user district 2 has been taken care of, a variable quantity of water q, $O \leq q \leq Q$, is available for transmission through reach 1 to

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3 "Dynamic Programming," by R. Bellman, Princeton University Press, New Jersey, 1957.

district 1. The problem is simply to determine how much of the amount q should be allocated to district 1. That is, the value of q_1 is desired as a function of the amount q which might be available after district 2 has been served, such that the net return is a maximum. Define this maximum return by f_1. Then

$$f_1(q) = \max_{\substack{O \leq q_1 \leq q \\ O \leq q \leq Q}} \left[v_1(q_1) - x_1 c_1(q)\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which x_1 is the length of reach 1 and $c_1(q_1)$ is the average annual cost per unit length of the aqueduct for reach 1 as a function of the required capacity for delivery of the quantity q_1.

Having thus "optimized" the allocation to the first district as a function of the available supply after district 2 has been served, attention may be turned to optimizing both districts 1 and 2. To deliver water to districts 1 and 2, water must be conveyed from the headgate of district 3 to district 2 over reach number 2. Presume that after district 3's needs under an optimum policy are met there is a variable quantity of water q, $O \leq q \leq Q$, available for allocation to districts 1 and 2. The problem here, then, is to allocate the quantity q in portions q_1 and q_2 so as to obtain maximum net beneficial return.

At this point use is made of the principle of optimality.[3] Whatever the decision may be regarding the allocation q_2, the remaining water $(q-q_2)$ must be used in an optimum manner if an optimum allocation is to be obtained.

Define f_2 (q) as the maximum net benefit from allocating water to districts 1 and 2 from the quantity available just downstream of the headgate for district 3. Then

$$f_2(q) = \max_{\substack{O \leq q_2 \leq q \\ O \leq q \leq Q}} \left[v_2(q_2) - x_2 c_2(q) + f_1(q - q_2)\right] \quad \ldots\ldots \quad (3)$$

Note that the cost of delivering $(q-q_2)$ to district 1 is already included in f_1. Thus the only additional cost is that of delivering q over reach 2 of length x_2.

The same reasoning can be applied with respect to district 1, 2, and 3. From an amount of water available just downstream of headgate of district 4, allocations can be made optimally to district 3 and districts 1 and 2 combined because the principle of optimality the suballocation of the combined allotment of districts 1 and 2 must be optimum and as given by Eq. 3.

Proceeding with this analysis over all districts in sequential order, there is the general recursive relationship

$$f_n(q) = \max_{\substack{O \leq q_n \leq q \\ O \leq q \leq Q}} \left[v_n(q_n) - x_n c_n(q) + f_{n-1}(q-q_n)\right] \quad \ldots\ldots \quad (4)$$

Solving Eq. 2 gives both $f_1(q)$ and $q_1(q)$. Solving Eq. 3 gives both $f_2(q)$, the optimum benefit from the last two districts on the line, and $q_2(q)$. Because the quantity left after q_2 is taken from q is $q-q_2$, the value of $q_1(q-q_2)$ is also obtained using the $q_1(q)$ previously obtained. Eq. 4 with n=3 gives both $f_3(q)$ and $q_3(q)$, thus giving q_3, q_2 and q_1 as functions of the quantity q available for these three districts. Eq. 4 also gives these values for n=4, 5, 6 . . . n. Finally $f_n(q) = V(q)$, the desired optimum value of q_n (q) the allocation to the n^{th} district as the head of the canal is obtained from which in reverse sequence the

TABLE 1.—ANNUAL BENEFIT AND COST FUNCTIONS[a,b]

q, in Acre feet (1)	$v_1(q)$, in dollars (2)	$v_2(q)$, in dollars (3)	$v_3(q)$, in dollars (4)	c(q), in dollars per mile[c] (5)
100	300	200	600	5.4
200	600	400	900	7.6
300	800	590	1100	9.3
400	980	760	1250	10.7
500	1150	930	1380	12.0
600	1310	1090	1500	13.2
700	1460	1240	1600	14.2
800	1600	1380	1690	15.2
900	1730	1515	1775	16.1
1000	1850	1645	1860	17.0
1100	1960	1775	1940	17.8
1200	2060	1900	1220	18.6
1300	2150	2020	1300	19.4
1400	2230	2130	1380	20.1
1500	2300	2230	1460	20.8
1600	2330	2420	1540	21.4
1700	2335	2510	1610	22.0
1800	2345	2600	1670	22.6

[a] Districts 1, 2 and 3
[b] All values in thousands
[c] These values hold for all parts of the aqueduct.

values of the various q_i can be taken directly from the corresponding functions.

The problem stated by Eq. 1 is now seen to have been transformed from an impossibly complex optimization involving one equation and n independent variables (the set of optimizing q_i) to a set of n recursive equations, each with only one unknown, Eq. 4.

Eq. 4 not only gives the optimum policy total net return, but by implication from the recursive analysis also gives the complete set of allocations q_i, all as functions of the quantity of water which might be made available in a range from zero to some arbitrary but logical upper limit. It must be stressed, however, that these are planning allocations prior to construction and are in no

way related to the allocation of limited supplies during drough periods from an aqueduct once constructed.

ILLUSTRATIVE PROBLEM

As an example of the method a hypothetical three stage allocation problem will be solved. An irrigation canal is to be designed to serve three geographic districts respectively located 30 miles, 50 miles and 75 miles downstream of

TABLE 2.–STAGE 1 OF SAMPLE CALCULATION[a,b]

Supply level q, in acre-feet (1)	Net benefit, $v_1(q_1)$, in dollars (2)	Cost of canal c(q), in dollars (3)	Net benefit, $F_1(q,q_1)$, in dollars (4)	$f_1(q)$, in dollars (5)	Allocation in Acre ft x 10^{-3} (6)
100	300	135	165	165	$q_1 = 100$
200	600	190	410	410	$q_1 = 200$
300	800	232	568	568	$q_1 = 300$
400	980	268	712	712	$q_1 = 400$
500	1150	300	850	850	$q_1 = 500$
600	1310	330	980	980	$q_1 = 600$
700	1460	355	1105	1105	$q_1 = 700$
800	1600	380	1220	1220	$q_1 = 800$
900	1730	402	1328	1328	$q_1 = 900$
1000	1850	425	1425	1425	$q_1 = 1000$
1100	1960	445	1515	1515	$q_1 = 1100$
1200	2060	465	1595	1595	$q_1 = 1200$
1300	2150	485	1665	1665	$q_1 = 1300$
1400	2230	503	1727	1727	$q_1 = 1400$
1500	2300	520	1780	1780	$q_1 = 1500$
1600	2330	537	1793	1793	$q_1 = 1600$
1700	2335	553	1782	1793	$q_1 = 1600$
1800	2345	568	1777	1793	$q_1 = 1600$

$$f_1(q) = \underset{0 \leq q_1 \leq q \leq Q}{\text{Max}}\ v_1(q_1) - x_1 c(q)$$

[a] All values in thousands. [b] x_1 = 25 miles.

the point of diversion respectively. For purposes of simplification it will be presumed here that deliveries for each district occur only at these specific points, that is, 30, 50 and 75 miles from point of diversion.

The available water supply will not exceed 1,800,000 acre ft and there may be question whether the entire amount should be diverted to this aqueduct. The seasonal demand is known so that acre feet per year demands can be related to cubic feet per second maximum capacity.

The costs per mile, again for the sake of simplicity, are presumed to be constant for a given capacity for all reaches of the canal. The cost per mile used is tabulated in Table 1.

The net benefit functions for the three geographic districts are also given in Table 1. Costs of distribution within the district have been deducted but aqueduct and other upstream costs have not.

The sample calculations begin with Table 2. This is a numerical solution of Eq. 2 of the text. The cost of 25 miles of canal (column 3) is deducted from

TABLE 3.—STAGE 2 OF SAMPLE CALCULATION[a,b]

q (1)	q_2 (2)	$q-q_2$ (3)	$f_1(q-q_2)$, in dollars (4)	$v_2(q_2)$, in dollars (5)	$z_2c(q)$, in dollars (6)	$f_2(q_1q_2)$, in dollars (7)	$f_2(q)$ (8)	Allocation, in acre ft x 10^{-3} (9)
100	0	100	165	0	108	57		$q_1 = 0$
	100	0	0	200	108	92	92	$q_2 = 100$
200	0	200	410	0	152	258	258	$q_1 = 200$
	100	100	165	200	152	213		$q_2 = 0$
	200	0	0	400	152	248		
300	0	300	568	0	186	382		$q_1 = 200$
	100	200	410	200	186	424	424	$q_2 = 100$
	200	100	165	400	186	379		
	300	0	0	590	186	404		
400	0	400	712	0	214	498		$q_1 = 200$
	100	300	568	200	214	554		$q_2 = 200$
	200	200	410	400	214	596	596	
	300	100	165	590	214	541		
	400	0	0	760	214	546		
500	0	500	850	0	240	610		$q_1 = 200$
	100	400	712	200	240	672		$q_2 = 300$
	200	300	568	400	240	728		
	300	200	410	590	240	760	760	
	400	100	165	760	240	685		
	500	0	0	930	240	690		
600	0	600	980	0	264	716		$q_1 = 300$
	100	500	850	200	264	786		$q_2 = 300$
	200	400	712	400	264	848		
	300	300	568	590	264	924	924	
	400	200	410	760	264	906		
	500	100	165	930	264	831		
	600	0	0	1,090	264	736		

$$f_2(q) = \underset{0 \leq x_2 \leq q \leq Q}{\text{Max}} \left[v_2(x_2) + f_1(q-x_2) - c(q)\right]$$

[a] All values in thousands.
[b] x_2 = 20 miles.

the net benefit (column 2) for each level of supply (column 1) to get the net benefit (column 4). From these values the allocations (column 6) which produce the maximum net benefit at each level of supply (column 5) are determined. Note that in this instance the allocation is equal to the supply up to 1,600,000 acre ft beyond which further allocation to district 1 would result in a loss.

Table 3 shows a portion of the second stage calculation. Here Eq. 3 is solved. $F_2(q,q_2)$ represents the net benefit resulting from the allocation q_2 to district 2 and the remainder $(q-q_2)$ to district 1. The maximum value of this function for each value of q is the desired value $f_2(q)$. The value of q_2 corresponding to this maximum is the proper allocation to district 2. The remaining water $(q-q_2)$ is allocated to district 1 in an optimum manner, already calculated in Table 2.

TABLE 4.—STAGE 3 OF SAMPLE CALCULATION[a,b]

q (1)	q_3 (2)	$q-q_3$ (3)	$f_2(q-q_3)$ (4)	$v_3(q_3)$ (5)	Z_3C (6)	$F_3(q,q_3)$ (7)	$f_3(q)$ (8)	Allocation, in acre feet x 10^{-3} (9)
100	0	100	92	0	162	-70		$q_3 = 100$
	100	0	0	600	162	438	438	$q_2 = q_1 = 0$
200	0	200	258	0	228	30		$q_1 = 0$
	100	100	92	600	228	464		$q_2 = 0$
	200	0	0	900	228	672	672	$q_3 = 200$
300	0	300	424	0	279	145		$q_1 = 0$
	100	200	258	600	279	579		$q_2 = 0$
	200	100	92	900	279	713		
	300	0	0	1100	279	821	821	$q_3 = 300$
400	0	400	596	0	321	275		$q_1 = 0$
	100	300	424	600	321	703		$q_2 = 0$
	200	200	258	900	321	837		$q_3 = 400$
	300	100	92	1100	321	871		
	400	0	0	1250	321	929	929	
500	0	500	760	0	360	400		$q_1 = 0$
	100	400	596	600	360	836		$q_2 = 0$
	200	300	424	900	360	964		$q_3 = 500$
	300	200	258	1100	360	998		
	400	100	92	1250	360	982		
	500	0	0	1380	360	1020	1020	
600	0	600	924	0	396	528		$q_1 = 200$
	100	500	760	600	396	964		$q_2 = 100$
	200	400	596	900	396	1100		$q_3 = 300$
	300	300	424	1100	396	1128	1128	
	400	200	258	1250	396	1112		
	500	100	92	1380	396	1076		
	600	0	0	1500	396	1104		

$$f_3(q) = \text{Max}\left[v_3(q_3) + f_2(q-q_3) - z_3C(q)\right]$$

$$0 \leq q_3 \leq q \leq Q$$

[a] All values in thousands.
[b] $x_3 = 30$ miles.

Note that as the number of units of water increases (18 units are shown in Table 2) the number of calculations to be made in the general case is one

more that the number of the unit. Thus if the total supply is subdivided into 20 units, the maximum number of net benefit calculations will be 2 + 3 + 4 + 5 + ... + 21 or a total of 230 for each stage past the first stage. If there were 20 districts potentially receiving water from this aqueduct a maximum of 4600 on line calculations would be required even for a hand calculation of a fairly complex system.

This number can be drastically reduced upon reaching a point at which for all higher values of q both benefit functions being considered are convex; that is monotonically decreasing functions of q. In this case the allocations can be determined very quickly from a table of increments for each function. The

TABLE 5.—FINAL ALLOCATIONS[a,b]

Acre feet available, q (1)	Allocations			Optimum net benefit, $f_3(q)$, in dollars (5)
	q_1 (2)	q_2 (3)	q_3 (4)	
100	0	0	100	438
200	0	0	200	672
300	0	0	300	821
400	0	0	400	929
500	0	0	500	1020
600	200	100	300	1128
700	200	200	300	1270
800	200	300	300	1404
900	300	300	300	1541
1000	300	300	400	1664
1100	200	500	400	1772
1200	200	600	400	1912
1300	300	600	400	2004
1400	300	700	400	2115
1500	300	700	500	2224
1600	400	700	500	2334
1700	400	800	500	2456
1800	500	800	500	2544

[a] Three stage aqueduct problem under an optimum benefit policy.
[b] All values in thousands.

optimum allocation for each q will be that which produces the largest increment of benefit for the increment in q.

Table 4 shows the third stage calculation. As an example for q = 600,000 acre ft available at the head of the aqueduct the maximum net benefit is obtained by allocating 300,000 acre ft to district number three and the remaining 300,000 acre ft to districts one and two combined. Entering Table 3 with the value 300,000 acre ft available at stage 2 the further allocation of 200,000 acre ft to district 1 and 100,000 acre ft to district 2 is obtained for optimum benefit policy.

The allocations cited in the previous paragraph are correct if only 600,000 acre ft were to be made available to this aqueduct. The problem postulated 1,800,000 acre ft as being available. If this is the case the calculations would

be continued as illustrated at least as far as q = 1,800,000 acre ft. The results of this calculation are shown in Table 5. The final allocations are q_1 = 500,000, q_2 = 800,000 and q_3 = 500,000 acre ft. The total benefit resulting will be $2,544,000.

Should it be desired to compare the benefits to be derived from diverting water to this aqueduct with the benefits from any other user, the values of $f_3(q)$ in Table 5 will provide the necessary information for an incremental analysis. Should comparison be desired with respect to a number of other alternatives a dynamic programming formulation similar to that presented here and elsewhere[2] can be made. Where applicable a linearization of $f_n(q)$ can be used in the formulation of a linear programming solution such as proposed by others.[4,5]

ANALYSIS

There are many aspects of this solution which might be examined. In the analysis it was tacitly presumed that accurate long range expected values of costs and benefits are obtainable. Admittedly some values are unobtainable and the accuracy of others will leave much to be desired.

The solutions obtained for the required capacities of an aqueduct as a function of reach under optimum return conditions must therefore be thought of as planning and design aids and not final operational allocations. Intangible social factors must be introduced before final actions are taken.

Some estimate of the intangible values can be made indirectly through this analysis because the solution covers a range of values of total water to be allocated. Thus, the difference between the optimum return and the return under any other plan under consideration for social objectives is a measure of the cost of the intangible social objectives. With knowledge of such cost in hand, if the legislative representatives of the population approved the social objectives, these objectives must at least be valued equal to the cost incurred.

A second important aspect of the solution for water development planning purposes is the form of the solution; that is, an optimal function instead of a single optimum value. Thus allocation problems to various aqueducts and other higher problems such as reservoir capacities may also be solved under optimum policy analysis using the aqueduct analysis as input benefit functions.[3]

A final important consideration is accuracy. No method of analysis is more accurate than the data used to arrive at conclusions. At the same time optimum policy analysis by dynamic programming gives maximum significance to the information at hand. Thus while it is admitted that the current state of the art in econometrics is not sufficient for accurate benefit and cost functions in the long range (50 yr or more), it must be conceded that decisions tempered by optimum policy analysis should more probably be accurate than a decision

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[4] "Design of the Simple Valley Project," by R. Dorfman, Harvard Water Resources Program, 1959, (Mimeographed).

[5] "Optimum Water Resource Development," by I. M. Lee, Giannini Foundation Report, No. 206, Univ. of California, 1958.

based on judgment allocations without regard to optimality but with benefits and costs computed on this same data.

CONCLUSIONS

A methodology has been presented for determining the proper allocation of water to the various geographic districts along an aqueduct such that the net benefit obtained is a maximum. With these allocations the aqueduct capacity required between diversions can be determined. A sample calculation for a three district system was used to illustrate the method.

The method is intended for development planning and in the form presented here it is not suited for such a problem as allocating water from an existing canal during dry years. The latter problem is recognized as one normally of equity or legal rights rather than an economic optimization.

The solutions obtained give the set of allocations resulting in maximum net benefit for all values of available water supply over an arbitrary range. Thus the results are quite useful in comparing this aqueduct's benefits with other possible diversions throughout a range. Such a comparison can be treated likewise by dynamic programming in those instances where the benefits are mutually independent.

As the cost of water resource development increases, the need for critical analysis to determine the best course of action becomes vital. Construction of public works is to a large extent irreversible, thus emphasizing the fundamental importance of maximizing the results of expenditures for water development. Dynamic programming offers considerable promise for such analyses.

ACKNOWLEDGMENT

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Journal of the
IRRIGATION AND DRAINAGE DIVISION
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IRRIGATION AND DRAINAGE STUDIES OF TEXAS RIVERS[a]

By Rolland F. Kaser,[1] F. ASCE

SYNOPSIS

A new approach to comprehensive planning for irrigation and drainage development, involving participation and collaboration by local, state and federal levels of government, is now underway in Texas. This study will evaluate potential developments from the standpoints of water and land resources and both local and national interests. It is being undertaken by the U. S. Study Commission-Texas, an agency created for that specific purpose. This paper is concerned principally with the Commission's Study Area, which includes the entire Gulf Coast of Texas and all of the area in Texas tributary thereto, except for that drained by the Rio Grande and the Sabine River.

Present and potential irrigation and drainage developments are summarized for the Study Area. The possible agricultural production in the area for the next 50 yr is analyzed and the role of irrigation and drainage in meeting future production goals is explained. It is concluded that the agricultural production of the Study Area in the year 2010 can supply a reasonable portion of the food and fiber requirements of a nation with a population of 380,000,000 people without additional water resource developments, by means of proven improvements in technology and easily-made changes in land use.

From the national standpoint there appears to be no compelling need to promote large-scale irrigation or drainage in the Study Area. However, local interests in some areas may prefer to undertake irrigation and drainage improvements instead of other means of increasing net economic returns from agricultural land use. In preparing its master plan for water resource develop-

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ment 50 yr ahead, the U. S. Study Commission-Texas must integrate these probable irrigation and drainage improvements with its plan for development of dependable water supplies for municipal and industrial use. At the same time, it must preserve supplies for existing irrigation and provide for other multiple purposes including flood control, navigation, hydroelectric power generation, recreation, and fish and wildlife conservation.

INTRODUCTION

Irrigation in Texas antedates the coming of the white man, as evidenced by traces of canal systems found along the Rio Grande. Notwithstanding this early beginning, extensive use of irrigation as a means of agricultural production in Texas is limited to the twentieth century and, in fact, to the years since World War II, during which large ground-water developments have been made. So rapid has been this increased use of irrigation in recent years, however, that the latest assessement of the acreage irrigated annually in Texas is 6,738,000 acres.

It has long been recognized that adequate drainage facilities could increase agricultural production from wetlands and could make possible the use of lands now largely swamp. Recent inventories have shown that a total of 6,493,000 acres of land situated along the Texas Gulf Coast and along the lower reaches of the major streams which drain to that area, could be made more productive by drainage improvements. For some years, there has been no major federal or state encouragement to drain lands for agricultural production, because crop surpluses are a national problem. The drainage actually done has been undertaken as private development as a land management technique to obtain increased net income from the land. Government subsidy or other support for drainage works has not been generally available.

Prior to 1959, planning for irrigation and drainage improvements in Texas was done on a local basis, and was undertaken by individual landowners, canal companies, irrigation and drainage districts, and federal agencies such as the Bureau of Reclamation, Soil Conservation Service, and Corps of Engineers. Each potential development was analyzed from a strictly local viewpoint. The facts that nearly all irrigable lands in the state are privately owned and that the costs of developing irrigation supplies in the arid portion of the State are high in comparison with such costs in other parts of the country, explain the scarcity of project-type developments thus far undertaken.

U. S. STUDY COMMISSION-TEXAS

In recognition of the need for comprehensive planning for water resource developments in Texas from a national as well as a regional or local standpoint, a new type of planning agency was created by Congress in 1958. Title II of Public Law 85-843, 85th Congress, approved August 28, 1958, created the United States Study Commission-Texas as an independent, temporary agency reporting to the Executive Office of the President. To assure the "grass roots" approach to comprehensive planning, the Commission includes nine commissioners (one from each of the eight major river basins in the Study Area and

one to represent the Texas State Bd. of Water Engrs.), who were nominated by the Governor of Texas and who report to him from time to time. Six other commissioners were appointed by the President from federal departments and agencies involved in water resource development, namely Dept. of the Army, Dept. of the Interior, Dept. of Agriculture, Dept. of Commerce, Dept. of Health, Education, and Welfare, and Federal Power Commission. The law specified that the chairman of the Commission, to be appointed by the President without specific nomination, must be a resident of the Study Area. This Commission, then, is made up of six commissioners who are full-time employees of established federal agencies, and ten commissioners, including the chairman, who were appointed from outside the federal government, and hold no other federal assignment. The commissioners all serve on a part-time basis.

In contrast to the agency dependency of federal interagency committees which have been formed in the past to aid in the coordination of water resource planning, the law which created the U. S. Study Commission-Texas provided for the employment of an independent staff to assist the Commission. In recognition of the fact that the originating law specified that maximum practical use would be made of the data and resources of existing agencies, the Commission elected to limit its professional staff to experienced engineers and planners required for review of basic data and studies performed by other agencies and for preparation of the Commission report. The staff includes 25 professional employees, mostly engineers, but includes also agricultural specialists, a ground-water geologist, an economic geographer, an economist, an attorney, and report writers. Supporting personnel, who perform secretarial, accounting, drafting, and related services, number 15.

The area assigned to the Commission for study includes the watersheds of all of the intrastate rivers of Texas and intervening areas tributary to the Gulf of Mexico in Texas. As shown in Fig. 1, this includes the drainage areas (from east to west) of the Neches, Trinity, San Jacinto, Brazos, Colorado, Guadalupe, San Antonio, and Nueces Rivers. Intervening areas include the watersheds of the San Bernard, Navidad, Lavaca, Mission, and Aransas Rivers. The Study Area includes about 62% of the land area of the state, and encompasses all that area of Texas which drains to the Gulf of Mexico through channels other than the Rio Grande and the Sabine River. The scope of this paper is limited to the Study Area of the U. S. Study Commission-Texas, the portion of the State with which the writer is familiar.

The planning procedure adopted by the Commission provided for two stages. First-stage planning was concerned with assessment of available basic data, its quality and usability for Commission purposes, identification of gaps in the basic data, consideration of ways and means of filling those gaps, and arrangements for the performance of work assignments by agencies having qualified personnel available to undertake work for the Commission. These work assignments involved the collection and adaptation of basic data on:

1. Surface-water runoff under existing and future conditions;
2. surface-water quality;
3. ground-water use and available supplies;
4. the land treatment and upstream watershed program;
5. forest land use and related industries;
6. existing irrigation and lands suitable for irrigation;
7. lands needing and feasible for drainage;

8. agricultural production requirements;
9. existing and projected municipal and industrial requirements;
10. hydroelectric power sites, energy requirements, and power values;
11. average annual flood damages under existing conditions; and
12. physical data and capacity-cost relationships for potential reservoir sites.

Agencies engaged to perform first-stage planning work assignments for the Commission included the Fort Worth and Galveston Districts of the Corps of Engrs., the Austin Development Office of the Bur. of Reclamation, the Fort

FIG. 1.—U. S. STUDY COMMISSION - TEXAS
THE STUDY AREA

Worth and Temple offices of the Soil Conservation Service, and Dallas office of the Public Health Service, the Fort Worth office of the Federal Power Comm., the Washington, D. C., office of the Agricultural Research Service, the Asheville, N. C., office of the Weather Bur., the Texas State Bd. of Water Engrs., the Bur. of Business Research of The Univ. of Texas, the Texas Agricultural Experiment Station, Texas Forest Service, Texas State Health Dept., and the Ground-Water Branch of the Geological Survey. First-stage planning work assignments included, in addition to development of other basic data, assess-

ment of future needs for water for municipal and industrial use and agricultural production requirements for the Study Area in the year 2010.

Thirteen collaboration groups, consisting of representatives of each of the federal and state agencies having an interest and technical knowledge in the specific subject or subjects with which the group was concerned, and chaired by a member of the Study Commission staff, were established to function as a part of the collaborative planning procedure. The groups were concerned with the identification of basic data needed, preparation or review of proposals for work assignments to be performed by other agencies, and technical review and comments on work performed for the Commission under work assignments. The collaboration groups made available to the Commission the professional talent and experience of the agencies involved in water resource planning in Texas; however, it should be understood that they were not work groups and served strictly in an advisory capacity. Work assignments to agencies, after approval by the Commission, were effected by contracts or memoranda of understanding between the Study Commission and the agency concerned. In the performance of these assignments, the performing agency served essentially in a consulting capacity to the client, the U. S. Study Commission-Texas. Agency work under these assignments was accomplished under the review and scrutiny of the Commission staff.

A higher level interagency committee, known as the Planning Coordinating Committee, and composed of experienced planners from the Texas State Bd. of Water Engrs. the Bur. of Reclamation, the Corps of Engrs., the Public Health Service, and the Soil Conservation Service, in addition to the Commission staff, was organized for technical review of collaboration group activities and of reports and other data prepared under work assignments. The Planning Coordinating Committee serves also as the collaboration group for technical review of second-stage planning activities, which include the development of preliminary intrabasin plans, the preparation of preliminary area-wide plans, and the refinement of data and estimates for projects included in the area-wide plan adopted by the Commission.

The first step in second-stage planning involved the preparation of intrabasin plans for each of the eight major river basins and adjacent intervening areas, to determine the most desirable plan for supplying municipal and industrial water requirements projected for the year 2010 from locally available water resources and, if additional water resources were found to be available for development, to determine the most desirable plan for developing such additional yields. The ultimate upstream watershed land treatment and flood water retarding structure program was considered and coordinated with these plans, because the effect of such programs on future runoff was taken into account in developing those data during first-stage planning. The intrabasin plans also took into account supplies of water needed for existing irrigation and for assumed future irrigation from surface water. The intrabasin plans were also coordinated with existing and assumed future uses of ground water.

Following completion of the intrabasin plans, it will be known which of the basins have water resources that will support the economical development of water yields, over and above the in-basin requirements, for export to water-deficient areas, and which basins have water resources inadequate to meet their own needs. The Commission must then determine the conditions under which interbasin transfers of water will be integrated in the area-wide plan to be recommended, in order that such a plan can be formulated. It should be

emphasized that the final plan to be recommended by the Commission in its report will be a comprehenisve, area-wide plan integrating all multiple-purpose features.

CLIMATIC CONDITIONS AND WATER REQUIREMENTS

It is often said that anything can be found in Texas, and this certainly applies to the climate of the Study Area. As shown in Fig. 2, the mean annual precipi-

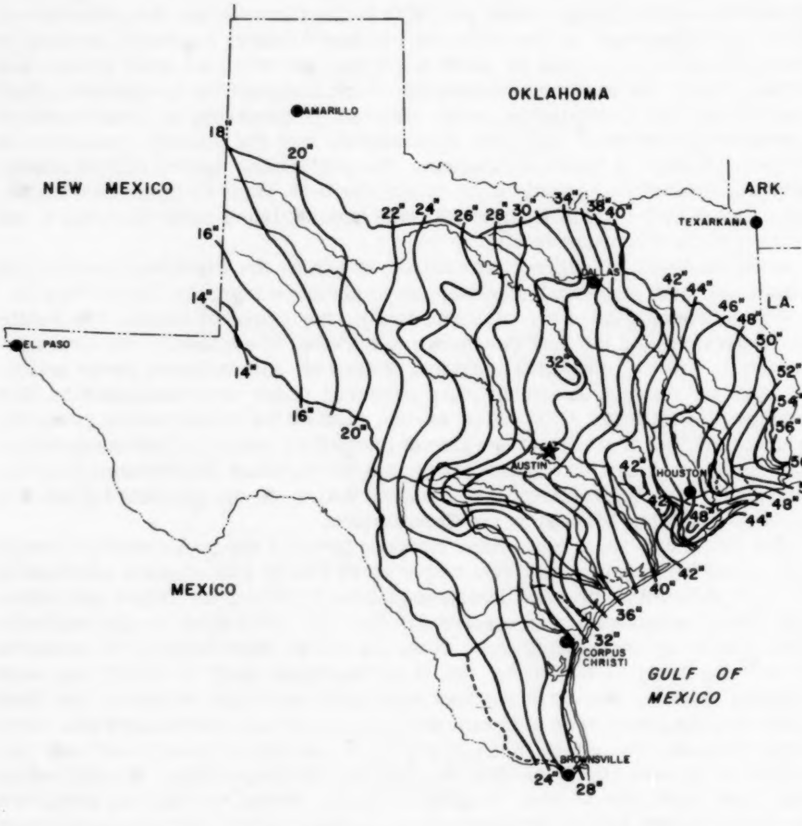

FIG. 2.—MEAN ANNUAL PRECIPITATION 1919-1957

tation varies from 56 in. near the Louisiana border to 14 in. in the High Plains near the New Mexico border. Fig. 3 is a graphic presentation of the average duration of the freeze-free season. It will be noted that the annual freeze-free season, which may be considered the season available for growth of crops, varies from 340 days in the extreme lower Rio Grande valley to 190 days in the upper portion of the Brazos River basin in the High Plains.

As might be expected from data shown on Figs. 2 and 3, the climate along the coastal plain from the mouth of the Guadalupe River through the lower reaches of the Neches River basin may be classed as humid subtropical. In this area, temperatures are comparatively warm with less variation during the year than occurs farther inland and with small changes from day to night. Precipitation in this area is moderate to plentiful at all seasons, with occasional very heavy tropical downpours. Skies are usually partly cloudy or cloudy and the average relative humidity is high in this coastal area.

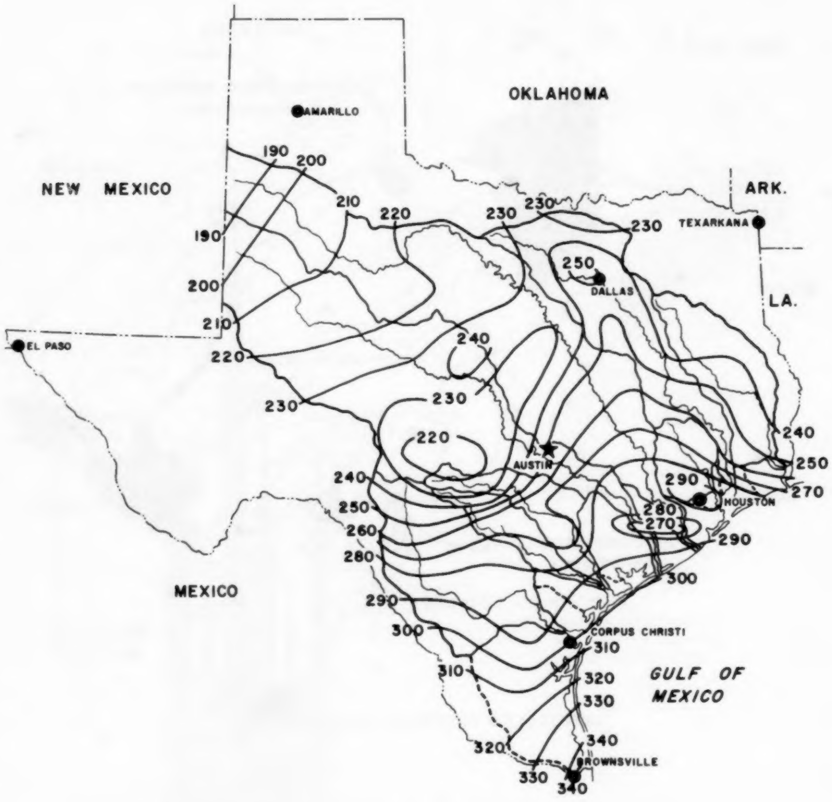

FIG. 3.—AVERAGE DURATION OF FREEZE-FREE SEASON IN DAYS 1919-1957

A semiarid continental climate exists at the headwaters of the Brazos and Colorado Rivers west of Abilene and San Angelo. In that High Plains area, precipitation is deficient and temperatures vary over a wide range from summer to winter. The temperature difference between day and night is also large. Hot summers, much sunshine, low humidity, and increased wind movement at ground level lead to high evaporation rates from exposed water surfaces.

Warm semiarid conditions are found in the southwest from the main stem of the Nueces southward to Brownsville. Precipitation is generally light compared to the high rate of evaportranspiration. However, on rare occasions, tropical storms produce very heavy rainfall. The climatic areas described do not have well-marked boundaries, but merge gradually from one to the other, as indicated on Figs. 2 and 3.

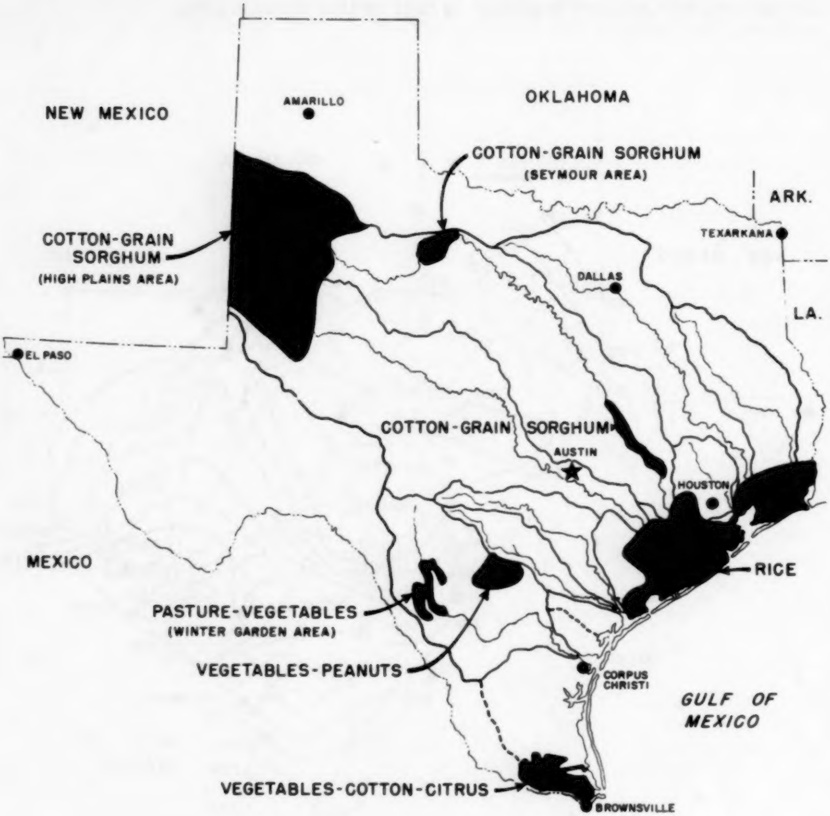

FIG. 4.—MAJOR CROPS IN PRINCIPAL IRRIGATED AREAS

The major crops grown in the principal irrigated areas of the Study Area are indicated on Fig. 4. As shown, cotton and grain sorghum are the principal crops in the High Plains, in the Seymour area, and in the river bottoms along the Brazos. Pasture and vegetables are the principal crops in the Winter Garden area south of Uvalde, and vegetables and peanuts are the principal crops in the Frio-Medina-Atascosa area west of San Antonio. Vegetables,

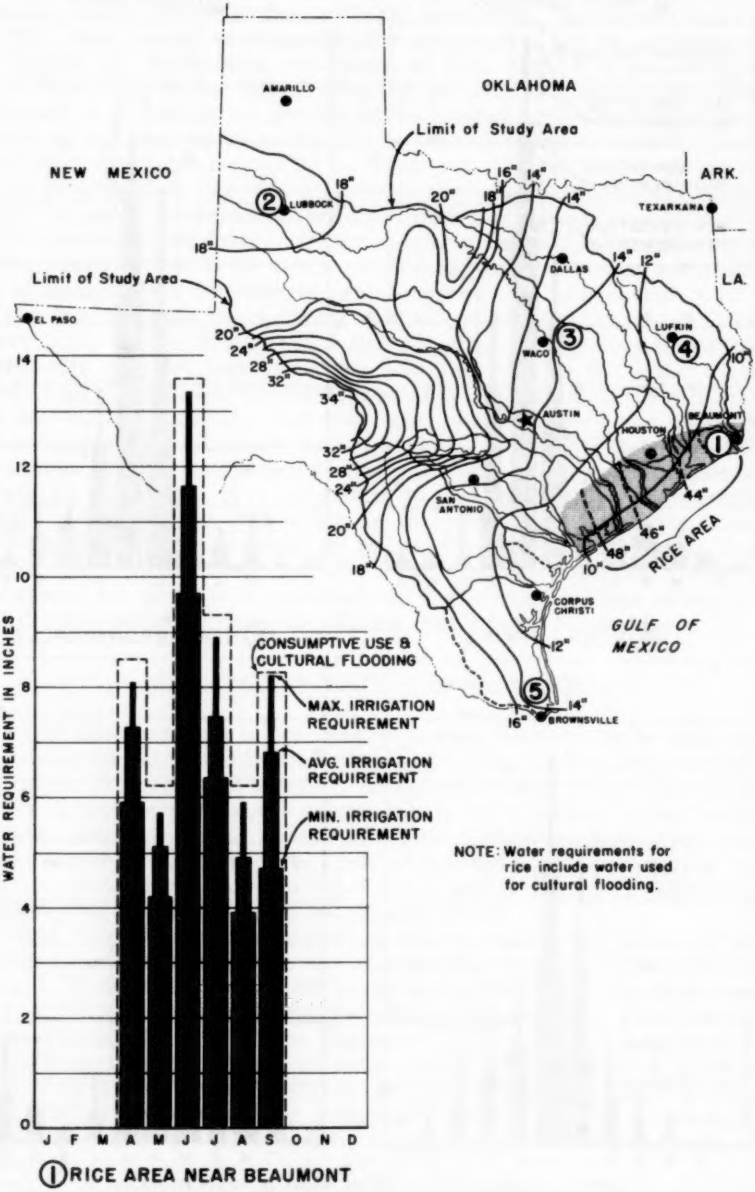

FIG. 5.—MEAN ANNUAL CONSUMPTIVE USE OF IRRIGATION WATER
1941-1957

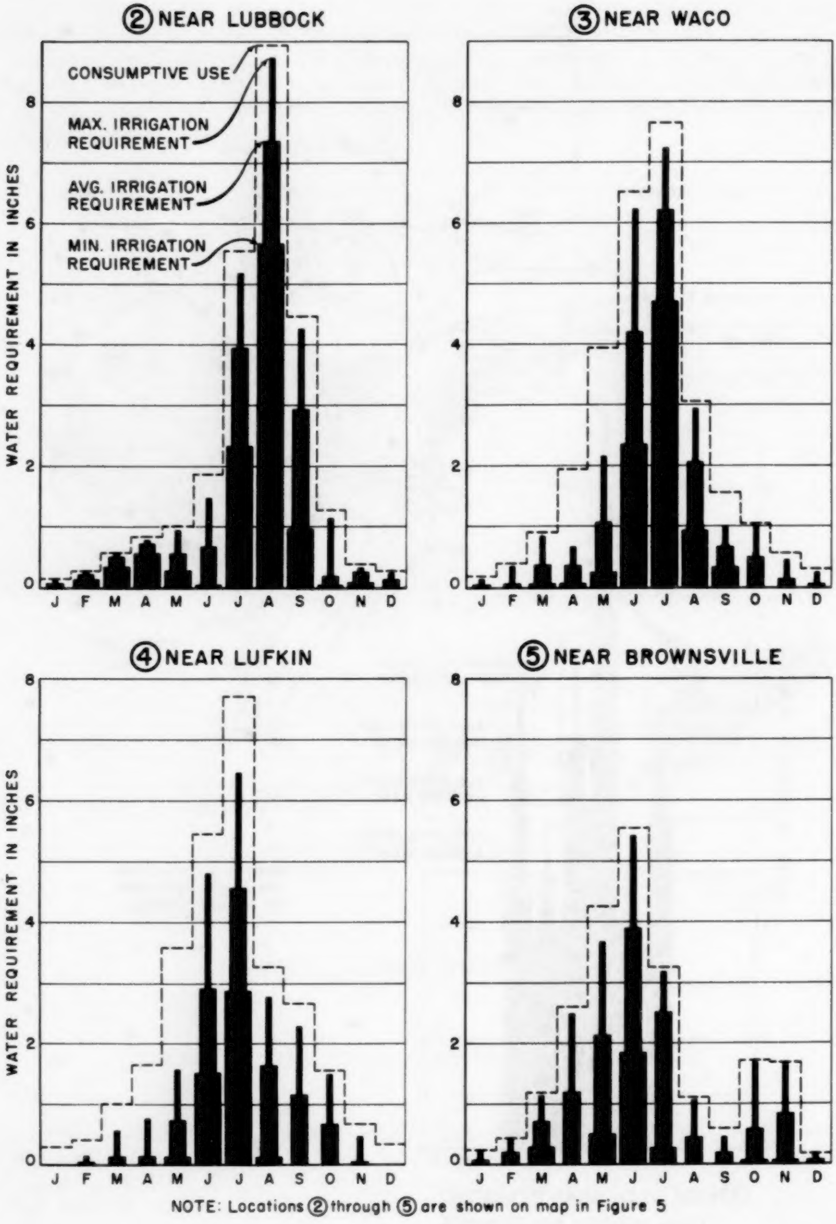

FIG. 6.—TYPICAL MONTHLY DISTRIBUTION OF IRRIGATION REQUIREMENTS 1941-1957

cotton, and citrus in that order are the principal crops in the lower Rio Grande valley. Rice is the principal crop along the eastern Gulf Coast.

The mean annual requirements for consumptive use of irrigation water throughout the Study Area are shown on Figs. 5 and 6. In developing those data, each crop in the typical cropping pattern for pertinent localities was analyzed to determine the portion of the total monthly consumptive use that would not be supplied by precipitation. The basic crop consumptive use data used were those determined by the Texas Bd. of Water Engrs. and published in its Bulletin 6019. The consumptive use requirement of irrigation water for each crop was thus determined, and a weighted value was obtained for the cropping pattern believed appropriate for each location. As might be expected from the explanation given of the climate of the area, consumptive use requirements for irrigation water for ordinary crops are lowest in the east Gulf Coast area of high humidity and precipitation, and are greatest in the middle Colorado River basin west of Austin. Fig. 5 shows that the average crop irrigation requirements vary for ordinary crops from 9 in. to 34 in. throughout the Study Area. Annual requirements for consumptive use of irrigation water for rice are also shown for the east Gulf Coast area, where rice is grown extensively. Because of the special nature of rice irrigation, in which the fields are flooded throughout most of the growing season, little effective use can be made of the natural precipitation. It is interesting to note that, while requirements for ordinary crops in that area would be approximately 9 in. to 11 in., rice requirements are from 43 in. to 49 in., or about four times as much. Part of this difference is due to the fact that the rice requirements listed are for 2010 conditions, for which it is assumed that the predominant type of rice grown will produce two crops from one planting over a 6-month period.

IRRIGATION INVENTORY OF STUDY AREA

It was disclosed early in Commission planning that no collected data existed concerning the extent and location of irrigation or of lands suitable for irrigation in the Study Area. Therefore, an assignment was given to the Soil Conservation Service to make an inventory of lands by water sources, irrigated in 1958, and of dry lands similar to lands currently irrigated. Figs. 7 and 8 show the general locations of the lands inventoried in those categories. Presently irrigated lands shown in Fig. 7 are identified as to the source of water supplies, that is, surface water and ground water.

Table 1 presents a summary of the data by major river basins and intervening areas which make up the Commission Study Area. As indicated in Table 1, of the total of 4,581,000 acres under irrigation in the Study Area in 1958, 3,524,000 acres were supplied solely by gound water. On a percentage of area basis, about 78% of the irrigation in the Study Area is supplied from ground water and only 22% from surface water. In addition to the lands irrigated in 1958, the inventory showed that there are about 18,250,000 acres of lands similar to those already irrigated, and suitable for irrigation if water could be provided. The latter total includes 2,122,000 acres of lands that have been irrigated in the past but were not irrigated in 1958.

The U. S. Study Commission-Texas has authorized the Texas State Bd. of Water Engrs. to include the irrigation inventory data reported by the Soil Conservation Service in its Bulletin 6018. The bulletin also includes similar

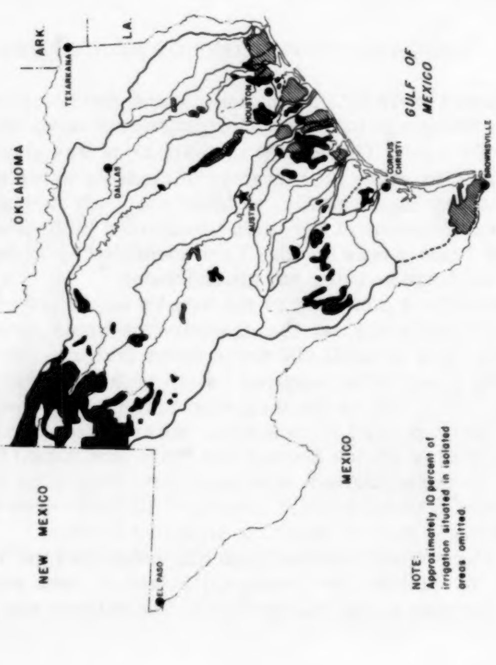

FIG. 7.—PRESENTLY IRRIGATED LAND BY SOURCE OF SUPPLY

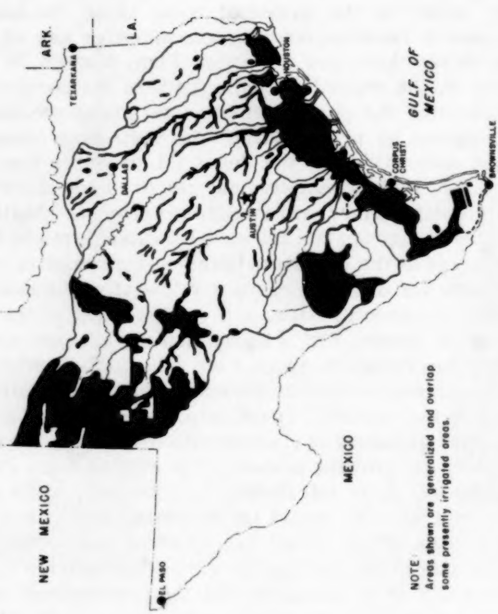

FIG. 8.—LOCATION OF LAND SUITABLE FOR FUTURE IRRIGATION (WATER AVAILABILITY NOT CONSIDERED)

TABLE 1.—SUMMARY OF 1958 IRRIGATION INVENTORY[a]

Area	Lands irrigated in 1958				Similar lands Suitable for Irrigation and Lands Prev. Irrigated but not in 1958
	From Surface Water	From Ground Water	From Both Sources	Total Irrigated in 1958	
(a) Neches River					
Physical basin	9.1	3.6	0.0	12.7	115.5
Adj. intervening areas	55.6	0.0	0.0	55.6	181.0
Total	64.7	3.6	0.0	68.3	296.5
(b) Trinity River					
Physical basin	19.7	7.3	0.5	27.5	899.1
Adj. intervening areas	39.0	0.0	1.3	40.3	194.5
Total	58.7	7.3	1.8	67.8	1,093.6
(c) San Jacinto River					
Physical basin	1.1	43.9	0.0	45.0	460.4
Adj. intervening areas	15.8	5.7	2.1	23.6	177.1
Total	16.9	49.6	2.1	68.6	637.5
(d) Brazos River					
Physical basin	38.1	2,605.1	10.5	2,653.7	2,867.1
Adj. intervening areas	38.7	6.9	0.6	46.2	468.6
Total	76.8	2,612.0	11.1	2,699.9	3,335.7
(e) Colorado River					
Physical basin	38.1	539.3	1.0	578.4	6,627.3
San Bernard River	21.7	7.7	2.8	32.2	358.9
Adj. intervening areas	27.8	23.6	5.4	56.8	804.2
Total	87.6	570.6	9.2	667.4	7,790.4
(f) Guadalupe River					
Physical basin	6.5	3.7	0.1	10.3	353.2
Lavaca-Navidad basin	18.3	54.9	1.6	74.8	458.5
Mission River	0.0	0.0	0.0	0.0	88.7
Adj. intervening areas	5.7	6.9	0.1	12.7	332.4
Total	30.5	65.5	1.8	97.8	1,232.8
(g) San Antonio River					
Basin Total	13.6	25.5	0.0	39.1	164.2
(h) Nueces River					
Physical basin	13.7	165.8	18.5	198.0	1,465.5
Aransas River	0.0	13.1	0.0	13.1	262.3
Baffin Bay area	4.2	3.3	0.0	7.5	996.6
Lower Coastal Bend area	11.5	2.2	0.0	13.7	740.5
Rio Grande valley	584.4	5.1	49.9	639.4	235.8
Total	613.8	189.5	68.4	871.7	3,700.7
Total Study Area	962.6	3,523.6	94.4	4,580.6	18,251.4

[a] Unit - Thousands of Acres

data developed by the Soil Conservation Service for areas in Texas outside the Study Area.

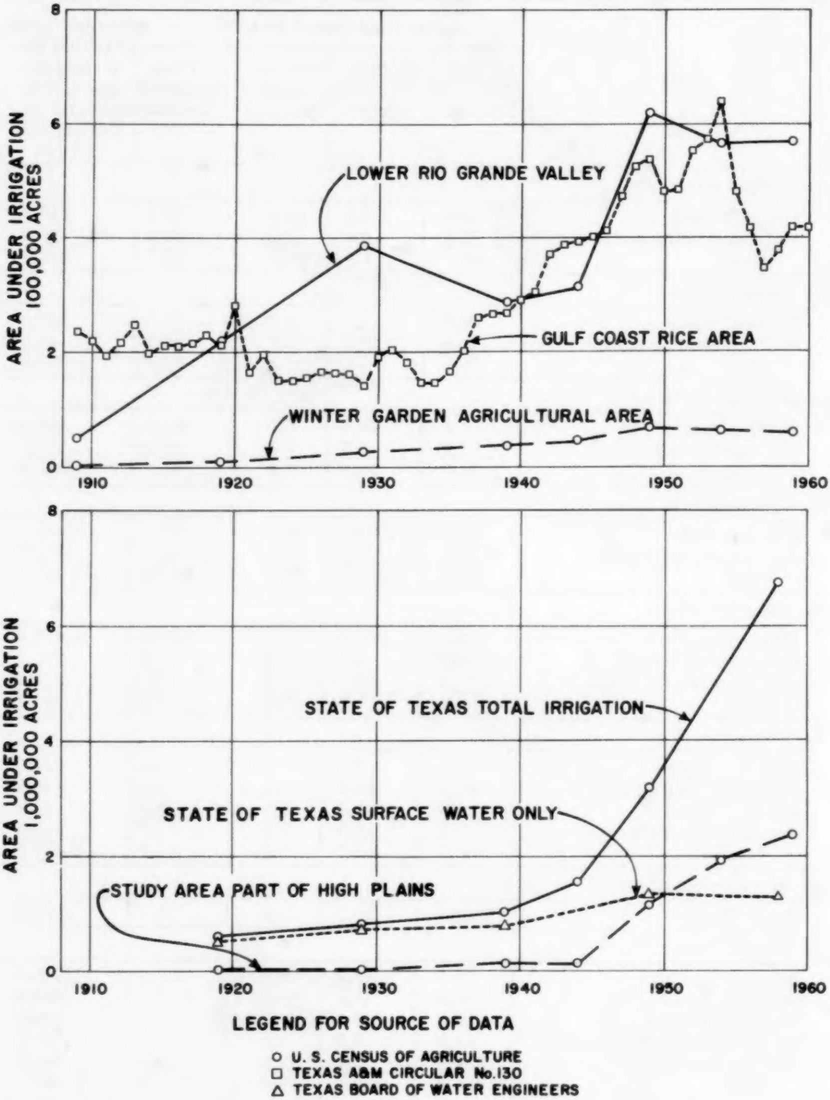

FIG. 9.—HISTORICAL GROWTH OF IRRIGATION IN TEXAS

Curves presented in Fig. 9 indicate the growth of irrigation in selected parts of the Study Area and in the state of Texas. The growth curve for the

entire state is presented since such data are not available for the Study Area, with which this paper is concerned. A comparison of the curve for total irrigation in the state with that for surface water only indicates that the latter has decreased since 1949, although the total irrigated acreage has more than doubled since that date. The difference between the two curves represents the ground-water irrigation, which amounted to only about 8 percent of the total irrigated area in 1919, but had gown to more than 80 percent of the state-wide total in 1958 because of the phenomenal ground-water developments in the High Plains. Growth curves are shown in Fig. 9 also for four major portions of the Study Area, namely, the lower Rio Grande valley, the Winter Garden area (near Carrizo Springs and Crystal City), the High Plains area, and the Gulf Coast area (rice only). The history and nature of irrigation in each of these major parts of the Study Area are summarized subsequently.

Modern irrigation in the Study Area began in the lower Rio Grande valley where vegetable and citrus crops were produced, and along the eastern Gulf Coast, where supplies of surface water were provided by canal companies for rice cultivation. At present, approximately 640,000 acres, planted mostly with cotton, grain sorghum, vegetables, and citrus, are now under irrigation in the lower Rio Grande valley.

Under present conditions (1961) rice is irrigated on about 420,000 acres annually in the east Gulf Coast area. Largely because of the limitation of rice production by agricultural quotas, only about one-fifth of the land under ditch and suitable for rice cultivation is now cropped each year. Experience has shown that if a crop of rice is grown no more often than one year out of three, the percentage of the undesirable red rice (which tends to increase with continuous rice production due to volunteer growth) can be controlled and a greater economic return obtained. During the years when the rice lands are not being cropped they are used for livestock pasture without benefit of irrigation.

Following World War II, extensive development of ground-water irrigation in the High Plains portion of the Colorado and Brazos River basins occurred. This development was made possible by the availability of:

1. Large volumes of ground water in storage in the Ogallala formation;
2. deep well turbine pumps;
3. cheap natural gas fuel for pumping engines; and
4. newly developed machines and technology which made possible the irrigation and associated high yields of cotton and grain sorghum.

It has been generally recognized for many years that this ground-water development in the High Plains consititutes a "mining" operation, since natural ground-water recharge is too small to be of consequence.

As shown in Table 1, a total of about 3,144,000 acres were under irrigation annually in 1958 from ground-water supplies in the Brazos and Colorado River basins and most (2,891,000 acres) of this was situated in the High Plains. On the basis of recently developed information concerning the magnitude of the ground-water storage and the present annual rate of consumptive use by irrigated crops in that area, it is apparent that the economically usable ground-water supply will be so nearly exhausted by the year 2010 that the High Plains area (except for isolated spots) can be expected to revert to dry-farming or ranching operations before that date.

Because the ground-water supply is being depleted at a rapid rate, measures are being taken to increase the efficiency of irrigation water use, such as construction of underground pipe distribution systems on the farms in lieu of

open ditches with high evaporation losses. Pumps are being installed in the "playa" lakes (lowest point in each of the many closed topographic basins in the area) in order that surface runoff thereto can be used when available—and before it evaporates—in lieu of ground water. This practice serves the same purpose as ground-water recharge and appears to be more practical than draining the lakes by wells, which lose their effectiveness rapidly unless the suspended sediment is removed before the water reaches the well. Such improvements in the efficiency of water use will make possible the irrigation of greater amounts of land in the High Plains or the continuation of irrigation of presently used lands for a longer period in the future. However, it is expected that only a nominal amount of irrigation will exist on the High Plains by the year 2010. The only present surface-water irrigation in the High Plains results from the disposal of the sewage effluent from major communities, such as Lubbock, for the irrigation of nonvegetable crops.

As shown by the curve in Fig. 9, the irrigated acreage in the Winter Garden area, which at its peak was one of the Nation's principal sources of winter vegetables, has declined in recent years. This decline has resulted from the lowering of the water levels to the point at which pumping was no longer economical, the increased salinity of the ground waters at the lower levels of the aquifer, the increased cost of farm labor for vegetable production, and the widespread use and distribution of frozen vegetables in recent years. The latter has tended to eliminate the advantage of areas with long growing seasons that can produce vegetables and other perishable crops during portions of the year when those crops cannot be grown elsewhere.

A situation similar to that in the High Plains has developed in the Seymour area of the Brazo River basin, where an area of approximately 40,000 acres has been developed, with ground-water supplies that are rapidly being depleted. Unlike the High Plains, it may be feasible to provide this area with a surface-water supply in order that it can continue in irrigated production. This matter will require further study to determine whether the water supplies which could be developed through storage in the Seymour area will be needed for higher priority uses and, if not, whether such an irrigation project would be economically advantageous.

Ground-water irrigation is increasing rapidly in an area situated between Uvalde and San Antonio, in the Nueces and San Antonio River basins, by pumping from the Edwards limestone aquifer. Sufficient irrigable land is available in that locality to use all of the dependable yield of the Edwards formation, which has been supplied historically by seepage into the Balcones Fault zone of almost all the surface runoff of the upper tributaries of the Nueces and Medina Rivers. Present trends for irrigation development in the area indicate that the irrigated acreage could increase from 52,000 acres in 1958 to approximately 150,000 acres in 1985. Should this development occur, the present water supply for the city of San Antonio would be largely cut off, and the flow of the Comal Spring (in the Guadalupe basin near New Braunfels), the natural spillway of the Edwards aquifer, which normally flows about 300 cfs, could be so reduced as to be of little dependability as a contribution to the surface-water supplies of the Guadalupe River.

As in most other humid portions of the United States, "insurance-type" irrigation is of increasing importance in the Neches and Trinity River basins as an element of modern, high level management for production of high value crops. Such irrigation, which is generally accomplished by sprinkler systems supplied by ground-water pumping, is expected to increase in the eastern

portion of the Study Area, but the acreage and water use involved therein will probably continue to be of relatively little importance compared to the acreages and water requirements of other irrigated areas in Texas.

DRAINAGE INVENTORY OF STUDY AREA

It was readily apparent at the outset of Commission planning that the location, areal extent, and characteristics of wetlands in the Commission Study

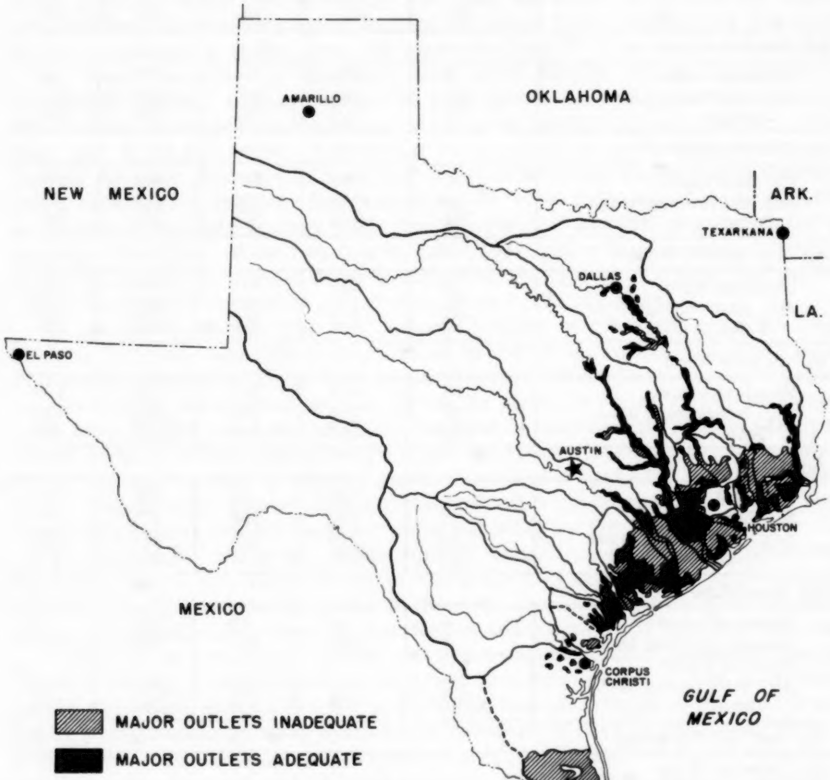

FIG. 10.—LOCATION OF LAND FEASIBLE FOR DRAINAGE

Area were inadequately known. Arrangements were made, by work assignment to the Soil Conservation Service, for an inventory of lands of limited usefulness because of inadequate drainage and for an investigaion of the economic feasibility of providing drainage facilities for those lands. As a result of this inventory, it was found that drainage was a problem on a total of 14,000,000 acres in the Study Area. About half of that area, 6,915,000 acres, was found to be

TABLE 2.—SUMMARY OF AREAS FEASIBLE FOR DRAINAGE[a]

Area	Presently Adequately Drained	Inadequately Drained			
		Needing Group Drainage	Needing Major Outlet Improvements	Needing on-farm Drainage	Presently in Cropland
(1)	(2)	(3)	(4)	(5)	(6)
(a) Neches River					
Physical basin	8	208	218	364	49
Adj. intervening area	43	104	106	246	165
Total	51	312	324	610	214
(b) Trinity River					
Physical basin	37	233	158	449	164
Adj. intervening area	19	79	105	225	156
Total	56	312	263	674	320
(c) San Jacinto River					
Physical basin	19	411	255	536	178
Adj. intervening areas	20	156	62	326	178
Total	39	567	317	862	356
(d) Brazos River					
Physical basin	123	424	237	734	299
Adj. intervening area	20	143	220	271	191
Total	143	567	457	1,005	490
(e) Colorado River					
Physical basin	3	196	54	240	136
San Bernard River	24	282	126	378	233
Adj. intervening areas	15	570	437	697	350
Total	42	1,048	617	1,315	719
(f) Guadalupe River					
Physical basin	6	43	43	125	51
Lavaca-Navidad basin	1	489	371	582	338
Mission River	7	1	0	7	1
Adj. intervening areas	51	417	224	573	235
Total	65	950	638	1,287	625
(g) San Antonio River	1	3	0	4	2
(h) Nueces River					
Physical basin	0	2	2	2	2
Aransas River	2	69	66	79	70
Baffin Bay area	11	43	0	44	35
Lower Coastal Bend area	0	48	61	61	36
Rio Grande valley	13	436	550	550	472
Total	26	598	679	736	615
Total Study Area	423	4,357	3,295	6,493	3,341

a Unit—1000 Acres

feasible for drainage. The portion of the entire drainage problem area which was not considered feasible for drainage included local areas that did not require drainage because of soils and topography, and lowlands adjacent to the Gulf and subject to periodic inundation by salt water or having brackish ground water near the surface.

The lands found feasible for drainage are indicated on the map in Fig. 10, which also indicates those lands requiring enlargement of natural major outlet channels in addition to other facilities to achieve effective drainage. It will be noted that the lands needing and feasible for drainage are situated in the coastal plain adjacent to the Gulf of Mexico and along the lower reaches of the major rivers. Table 2 presents a summary of the areas found feasible for drainage in the Commission Study Area. As shown in Table 2 of the total of 6,916,000 acres found feasible for drainage, only about 423,000 acres are presently adequately drained, although numerous past efforts have given partial protection to large acreages. Of the total that is inadequately drained, slightly more than half, 3,341,000 acres, is presently in cropland, but production thereon is limited by poor drainage. The remaining portion of the inadequately drained lands feasible for drainage are in pasture and woodlands. All of the 6,493,000 acres of inadequately drained lands feasible for drainage will require on-farm drainage facilities. About two-thirds, 4,357,000 acres, will need group drainage laterals to convey effluent from the farm drains to major outlets, and major outlet improvements will be required to drain 3,295,000 acres.

It should be recognized that a large portion of the wetlands on the Gulf Coastal Plain are lowlands characterized by a high water table and heavy soils of very low permeability. In their present condition these lands can be cropped in rice under the system used in Texas, in which a crop of rice is produced each 3 to 5 yr, and in intervening years the land is used for unirrigated pasture. Under present trends toward future urban and industrial expansion, it appears likely that approximately 590,000 acres of the total of 6,493,000 acres of presently inadequately drained land found feasible for drainage will be withdrawn from agricultural use and used for those purposes by the year 2010.

In addition to the lands inventoried as being in need of and feasible for drainage, there are many acres of flood plain lands along the major water courses which, because of frequent flooding, are limited to uses which will not be rendered uneconomic by the degree and frequency of flooding that can be expected. In this paper, lands that are frequently wet or inundated due to rainfall on the land itself are considered in need of drainage, and lands that suffer the same sort of damage due to flood waters brought to the area from heavy precipitation on other lands are considered in need of flood control improvements. Undoubtedly, the comprehensive plan to be formulated for water resource development and utilization in the Study Area to the year 2010 will include many multiple-purpose storage facilities that will eliminate or reduce the flooding potential on flood plain lands. It is probable that when the Commission planning and plan formulation have progressed to the point that lands which will benefit from flood damage abatement have been determined, it will be found that some of those lands will require drainage improvements in order to permit optimum agricultural production thereon.

FUTURE IRRIGATION AND DRAINAGE

In planning for irrigation and drainage development from a national as well as a regional viewpoint, it is necessary to ascertain the agricultural production

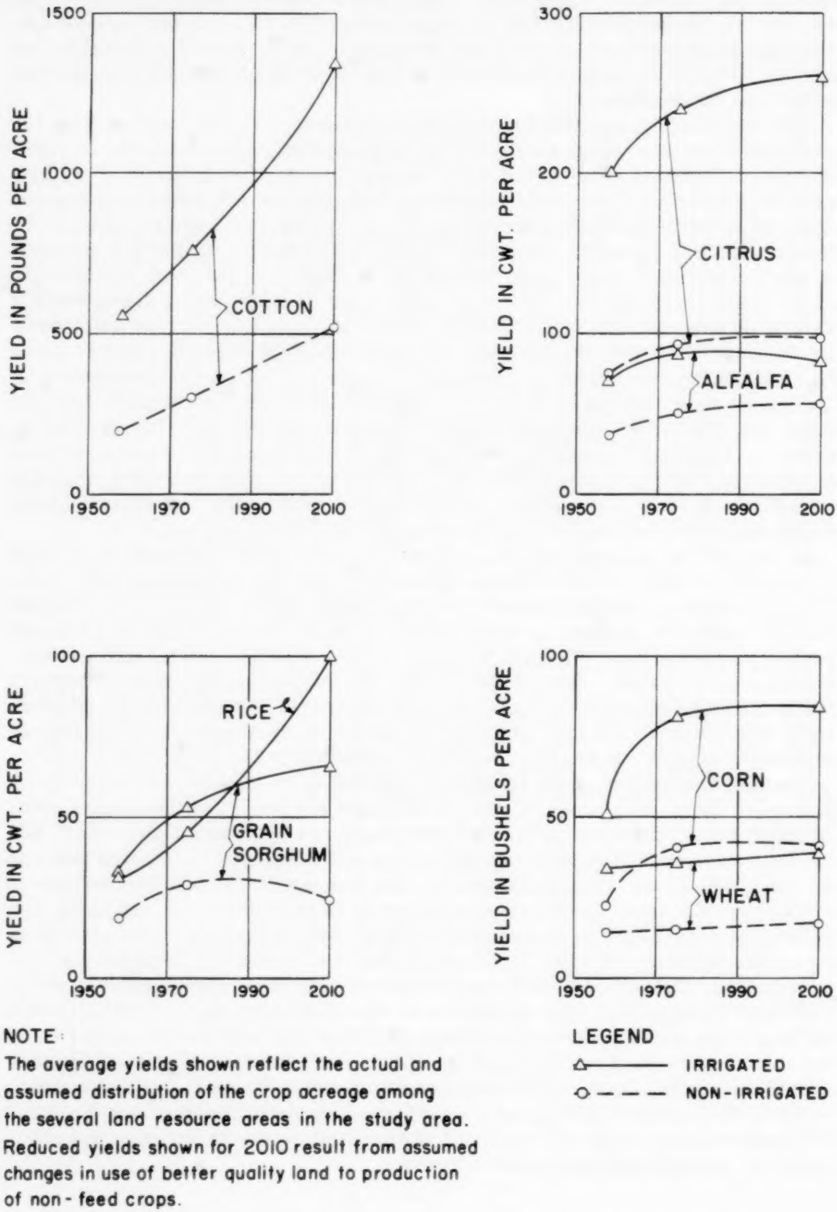

FIG. 11.—EXISTING AND PROJECTED CROP YIELDS AVERAGES FOR THE STUDY AREA

that the area under study might be called upon to produce as its share of the national, as well as of the local, requirements for food and fiber. Another necessary step is the estimation of the agricultural production which may be achieved through improved technology, use of fertilizers, reasonable adjustments in land use, and other factors exclusive of new water resource improvements. However, such estimates are "easier said than done."

The Study Commission has engaged the Agricultural Research Service of the Dept. of Agriculture to develop agricultural production goals for the Study Area 50 yr in the future. The Soil Conservation Service compiled, for use in the ARS study, information concerning present land use and present crop yields throughout the Study Area. Information on future crop yields and livestock feeding efficiencies were compiled by the Texas Agricultural Experiment Station, a unit of the Texas A & M College System. In projecting agricultural yields 50 yr in the future, allowances were made for the increased yields which can reasonably be expected because of the use of improved varieties of crops and management techniques that have been proven practicable by reliable testing. Curves showing the present and projected future normalized yields of major crops grown in the Study Area are presented on Fig. 11. In estimating future yields without irrigation, only those rates of fertilizer application that could be made without irrigation were considered. As an example of these considerations, it was found that although the present yield of rice averages about 3,100 lb per acre, the yield in 2010 is expected to be about 9,900 lb per acre. The future yield estimate is predicated on the availability and widespread use by 2010 of new varieties of rice that will produce two crops of grain in a six-month period from one planting.

In estimating the agricultural production that could be realized from the Study Area in the year 2010 without new water resource developments, it was necessary to make allowance for the withdrawal from agricultural use of lands that may be expected to be used for urban or industrial expansion. Study Commission planning is being done for a population increase in the Study Area of from 7,850,000 people in 1960 to over 19 million people in 2010. Under those conditions nonagricultural uses of land, which amounted to about 3,360,000 acres in 1958, could increase to about 10,000,000 acres in 2010. Most of this new nonagricultural use of land will occur near the metropolitan centers of Fort Worth, Dallas, Beaumont, Houston, Corpus Christi, and San Antonio, and at other points suitable for major industrial expansion along the Gulf Coast. In the coastal prairie area alone, for example, about 600,000 acres of land are presently in nonagricultural use (cities, industrial plants, and roads), and those uses are expected to require about 2,550,000 acres in 2010.

Another important factor for consideration was the probable curtailment or elimination of irrigation before 2010 in the High Plains and in other areas where the ground-water supply is being mined. Experts of the Agricultural Research Service, in assessing the portion of the national food and fiber production requirement to be expected from the Study Area in 2010, (assuming an increase in population from the 1960 level of 180,000,000 to 380,000,000 in 2010), were able to extend the information and procedures they had developed for the Select Committee on National Water Resources of the U. S. Senate (Kerr Committee). For all portions of the United States likely to produce the same or competitive crops, it would have been desirable to have developed the same sort of detailed information as has been developed for the Study Area. Since this has not been possible, it has been necessary to rely on the

experienced impartial judgment of the experts of the Dept. of Agriculture in determination of production goals for the Study Area in 2010 for each significant crop or crop group. These data are summarized in Table 3.

It has been concluded that the agricultural production goals established for the Study Area for the year 2010 represent a reasonable portion of the food and fiber requirement of the nation, and that these goals could be met without additional water resource developments by application of proven improvements in technology and changes in land use that might readily be made by landowners at reasonable conversion and crop production costs. It would appear, then, that from the national standpoint there is not compelling reason to promote large scale irrigation or drainage projects in the Study Area. This should not be interpreted to mean that new irrigation and drainage developments will not, or should not, be constructed in the area in the future.

Data presented in Fig. 12 indicate that in portions of the Study Area a sizeable increase in net farm income per acre can be achieved through irrigation. Possibly of greater importance is the fact that the increased net annual farm income that can be realized through drainage is estimated to exceed the annual cost of the improvements by a sizeable margin. Under these circumstances, some agricultural interests may be expected to prefer irrigation and drainage improvements over alternative land use changes, where opportunities exist and it is to their economic advantage.

TABLE 3.—NORMALIZED AGRICULTURAL PRODUCTION (1958)[a] AND GOALS FOR YEAR 2010 FOR STUDY AREA

Crop or Crop Group (1)	Units (2)	Normalized Production 1958 (3)	Production Goal - 2010 (4)
Citrus	Thousand cwt	11,700	27,200
Vegetables	Thousand cwt	20,327	40,100
Rice	Thousand cwt	14,540	24,500
Cotton	Thousand cwt	13,600	32,200
Oil crops	Thousand cwt	1,850	6,500
Wheat	Thousand bu	23,860	46,000
Feed & Forage	Thousand tons of feed units[b]	18,500	27,300

[a] Differs from actual production in 1958 by adjustments to remove effects of special circumstances not believed typical of general 1958 level of production.
[b] A feed unit is one pound of corn or its feeding equivalent.

The economic opportunities of pump irrigation have been demonstrated convincingly on the Texas High Plains, in other parts of the West and in many areas unexploited ground water underlies irrigable lands. In some places it may be possible to develop surface-water supplies, by a multiple-purpose project, at costs within the ability of irrigators to repay. In other areas it may be expected that developments and use for municipal and industrial purposes will make available return flow waters in sufficient quantity to provide a dependable supply of water for irrigation. In the latter cases, organic pollution

in the return flows may preclude the use of the water for irrigation of vegetables.

Under these circumstances, the Study Commission must prepare its comprehensive plan on the basis of its best analysis of expected local developments in irrigation and drainage improvements. It must fit other developments

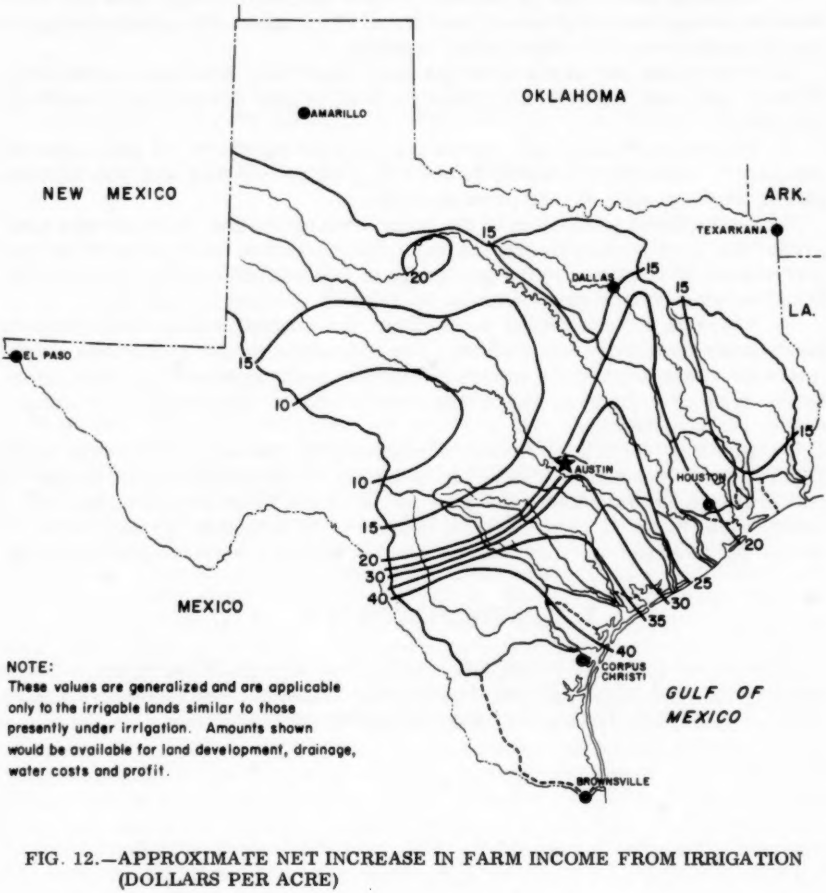

FIG. 12.—APPROXIMATE NET INCREASE IN FARM INCOME FROM IRRIGATION (DOLLARS PER ACRE)

into that framework rather than to strive to include projects in the comprehensive plan specifically to increase agricultural production.

CONCLUSIONS

1. The acreage of crops irrigated each year in the State of Texas has increased from about one million acres at the start of World War II to 6,750,000

acres in 1958. Of this area, 4,600,000 acres (68%) are in the Study Area of the U. S. Study Commission—Texas.

2. Ground-water irrigation in the High Plains of Texas, which has been developed since World War II and comprises more than half of the 4,600,000 acres irrigated in the study area in 1958, is a "mining" operation which will exhaust its economically usable water supply within the next 50 yr.

3. Although more than 18,000,000 acres of land in the study area are suitable for irrigation, only a small portion of those lands will ever be irrigated due to limitations of available water supplies.

4. Over 6,000,000 acres along the east Texas Gulf Coast are inadequately drained and are feasible for drainage. Half of that acreage is presently in cropland.

5. Present technology and proven management practices not yet in general use may be expected to result in future crop yields, both with and without irrigation, which greatly exceed present yields.

6. Agricultural production in the Study Area for the next 50 years can meet production goals, representing an equitable portion of the food and fiber requirements of a nation with a population of 380,000,000 people, without additional water resource developments, by feasible changes in land use.

7. There is no compelling need, from the national standpoint, to promote large-scale irrigation or drainage improvements in the study area. Local interests, however, may be expected to prefer such improvements over alternative land use changes, where opportunities exist and economic advantages can be realized thereby.

8. Planning for water resource utilization in the area of concern to the U. S. Study Commission—Texas can be based on: (a) projections of irrigation and drainage improvements that may be developed by or for the people of the area on the basis of local desires; instead of (b) a need for project developments to increase agricultural production to meet national requirements.

ACKNOWLEDGMENTS

This paper presents views and conclusions for which the writer alone is responsible and which do not necessarily represent the views of the U. S. Study Commission-Texas, or of any commissioner thereof.

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CONSUMPTIVE USE AND WATER WASTE BY PHREATOPHYTES[a]

By Harry F. Blaney,[1] F. ASCE

SYNOPSIS

Phreatophytes are vigorous, water-loving plants ranging from small natural vegetation to large saltcedar (tamarisk) and cottonwood trees. These plants habitually obtain their water supply from the zone of saturation, either directly or through the capillary fringe in areas of high ground water. Although phreatophytes occur in all regions of the United States, they are the greatest menace in the areas of limited water supplies in the Southwest States, where they occupy large areas along stream and river channels, on flood plains and in areas of high water table. These plants are spreading rapidly, and are consuming and wasting large quantities of water that could be put to beneficial use for irrigation, domestic, and industrial purposes. Dense growth of phreatophytes causes accumulation of sediment, blocks river channels, and increases flood hazards. Studies by the United States Department of Agriculture of consumptive use (evapotranspiration) indicate that saltcedar and cottonwoods use from 50% to 100% more water than most agricultural crops. Estimates based on incomplete data indicate that phreatophytes cover about 16 million acres in the western half of the United States, and consume nearly 25 million acre-ft of water annually. Preliminary studies by the writer in California and New Mexico indicate that about 25% to 50% of consumptive use and waste by these water-loving plants may be saved for beneficial uses by elimination of saltcedar and cottonwoods.

Note.—Discussion open until February 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. IR 3, September, 1961.

[a] Presented at the April 1961 ASCE Convention in Phoenix, Ariz.

[1] Irrig. Engrg., U. S. Dept. of Agri., Los Angeles, Calif.; also member of Subcommittee on Phreatophytes, Pacific Southwest Inter-Agency Committee.

Results of measurements of consumptive use by phreatophytes are presented; a method of estimating rates of water consumption for areas in which no measurements are available is described; and the amount of water that may be salvaged by controlling phreatophytic vegetation is estimated.

INTRODUCTION

Engineers and hydrologists, when making an inventory of available water supply of a river basin for irrigation and other water projects, should give careful consideration to consideration to consumptive use and waste of water by phreatophytes and hydrophytes before new projects are authorized. The term "consumptive use" in this paper is considered synonymous with the term "evapotranspiration" and is defined briefly as the quantity of water evaporated and transpired from an area. Measurements by the writer and others indicate the water consumed by phreatophytes ranges from about 1 acre-ft to 7.5 acre-ft per acre (12 in. to 90 in.) annually.

Phreatophytes (well plants) are plants that habitually grow where they can send their roots down to the water table or the capillary fringe immediately overlying the water table.[2] These plants, such as saltcedar (tamarisk), cottonwood, willow, and saltgrass grow in areas of high-water table along stream and river channels, lake borders, or canals.

Hydrophytes are plants that live wholly or partly submerged in water, or with roots in saturated soil that is intermittently submerged, such as tules, cattails, and other marsh plants growing in swamp areas, lake borders, river channels, or drainage and irrigation canals.

The line between hydrophytes and phreatophytes is not always sharp. At times a few phreatophytic and hydrophytic plant groups overlap in their relationship to water table. In some areas, hydrophytes such as tules and cattails have a greater rate of consumptive use of water than saltcedars and cottonwoods.

These water-loving plants are creating serious problems in Western United States. In many areas, surface and ground water supplies are limited; and demands for water, already great, are increasing for irrigation, domestic, and industrial purposes. With reference to water use by saltcedar the Water Resources Review of the United States Geological Survey, Dept. of Interior (U.S.G.S.) September, 1960 stated:

> "Its rate of increase is so rapid that if the present rate continues through the next 20 years, saltcedar easily could use up all the water in the affected streams of the Southwest."

The moisture requirements of these natural plants are usually satisfied before water becomes available for irrigation and other purposes. Measurements of evapotranspiration indicate that some water-loving natural vegetation use from 50% to 100% more water than most crop plants. Saltcedar, cottonwoods, and tules growing in irrigation canals and drainage ditches and on their

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[2] "Outline of Ground Water Hydrology, With Definitions," by O. E. Meinzer, Water Supply Paper No. 494, U.S.G.S., Dept of The Interior, Denver, Colo., 1923.

banks are exposed in narrow strips to sun and wind so that their consumption water is unusually high.

Since about 1935, consumptive use (evapotranspiration) by phreatophytes has become an important factor in the arbitration of controversies over water rights of major stream systems such as the Rio Grande,[3] Pecos River and Colorado River.[4] As early as 1927, engineers of the United States Department of Agriculture and the State of California foresaw that the water wasted by phreatophytes and hydrophytes would be needed for additional water supply in Southern California. Then, and at various times since 1927, the writer and associates were assigned to measure the consumptive use by several water-loving plants growing in the Southwestern United States.[5] The results of some of these studies are presented in this paper.

FACTORS AFFECTING WATER USE

Many factors operate singly or in combination to influence the amount of water consumed by plants. Measurements of transpiration of various kinds of plants indicate a close correlation between transpiration, evaporation, temperature, solar radiation, and humidity.

Factors that affect the rates of consumptive use by phreatophytes include (a) available water supply, (b) depth to water table, (c) climate, (d) density of plant growth, (e) quality of water, and (f) soil. Usually, the shallower the water table, the higher the rate of use. For some species, the depth to ground water is the controlling factor of their occurrence and growth. In soils of fine texture, the height of the capillary fringe is greater than in soils of coarse texture. Climatic conditions control the occurrence and growth of some species, whereas others are relatively unaffected by climate.

CONSUMPTIVE USE MEASUREMENTS

Measurements of water consumption have been made by Federal and State agencies in several areas. However, the observations are limited, and no long-term records are available. For example, data on water use by saltcedar covers only periods of from $\frac{1}{2}$ yr to 1 yr at different sites. Also, more research is needed on water use under different climatic and soil conditions. Therefore, it is usually necessary to estimate consumptive use in most river basins by empirical formulas.[6]

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[3] "Water Utilization, Upper Rio Grande Basin," by Harry F. Blaney, Paul A. Ewing, O. W. Israelsen, C. Rohwer, and F. C. Scobey, Natl. Resources Committee, Part III, 1938.

[4] "Consumptive Use of Water Rates in the Lower Colorado River Basin," by Harry F. Blaney and Karl Harris, Appendix B, Report on Water Supply of the Lower Colorado River Basin, U. S. Bur. of Reclam., Dept. of The Interior, Denver, Colo., November, 1952.

[5] "Water Losses Under Natural Conditions from Wet Areas in Southern California," by Harry F. Blaney and C. A. Taylor, Bulletin 44, Calif. State Dept. Pub. Works, Div. of Water Resources, 1933.

[6] "Consumptive Use of Water in the Irrigated Areas of the Upper Colorado River Basin," by Harry F. Blaney and Wayne D. Criddle, Soil Conserv. Service, U. S. Dept. of Agric., Washington, D. C., 1948.

The relationship between consumptive use by cottonwoods and other native vegetation and depth to water table in the San Luis Rey Basin, Calif., based on a 5-yr study,[7] is illustrated in Fig. 1. Points shown on the curve are the results of the following annual measurements of water use: "A"—2 years' record from a tank 6 ft in diameter and 6 ft deep, growing cottonwood with water table at 3 ft; "B"—3 years' record from similar tank with cottonwood growing with water table at 4 ft; "C"—field observations on grassland where depth to water table was 12 ft; and "D"—field records on grass-brush area where the average depth to water table was 4.7 ft below the ground surface.

Rates of evapotranspiration losses by phreatophytes and hydrophytes growing in areas on high-water table have been measured by means of tanks, lysimeters, inflow-outflow, ground-water fluctuations, and other methods. At

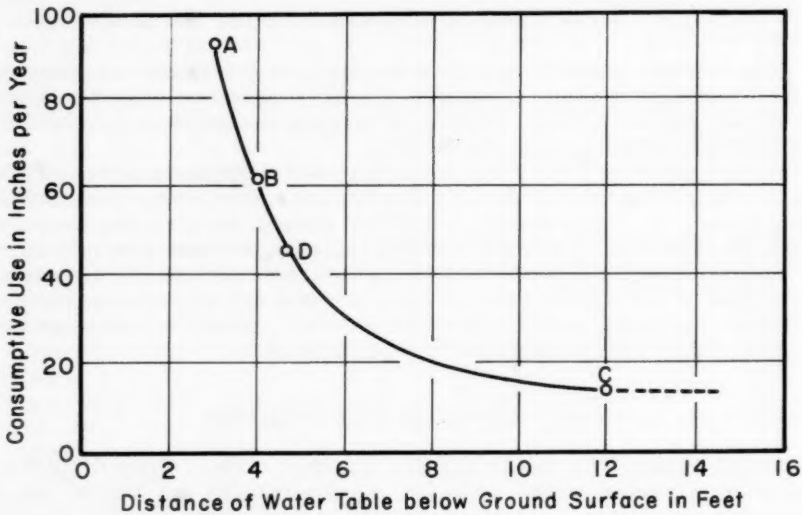

FIG. 1.—CONSUMPTIVE USE BY NATIVE VEGETATION SAN LUIS REY VALLEY, CALIF.

various times since 1928, the writer has measured rates of consumptive use in California, Colorado, New Mexico, and Texas.[8] The results of some of these measurements, and of those made by other investigators, are shown in Table 1.

ESTIMATING CONSUMPTIVE USE

Actual measurements of consumptive use under each of the physical and climatic conditions of any large area are expensive and time-consuming. The results of research and measurements of the consumptive use of water, along

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7 "Utilization of the Waters of Lower San Luis Rey Valley, San Diego County, Calif.," by Dean C. Muckel and Harry F. Blaney, U. S. Dept. of Agric., Washington, D. C., 1948.

8 "Use of Water by Native Vegetation," by Arthur A. Young and Harry F. Blaney, Bulletin 50, Calif. State Div. of Water Resources, 1942.

with meteorological observations, provide basic data required for estimating consumptive use by phreatophytes for areas in which no water-use data are available.

Several formulas have been developed for determining water consumption. One commonly used for computing water losses by phreatophytes in large river

TABLE 1.—ANNUAL OR SEASONAL CONSUMPTIVE USE OF GROUND WATER BY PHREATOPHYTES AND HYDROPHYTES

Locality (1)	Type (2)	Period (3)	Depth to water table, in inches (4)	Consumptive use, in inches (5)
ARIZONA				
Safford	Saltcedars[a]	Sept. 1943-Oct. 1944	--	86.4[b]
Safford	Cottonwoods[a]	Sept. 1943-Oct. 1944	--	72.0[b]
Safford	Baccaris	Sept. 1943-Oct. 1944	--	56.4[b]
Safford	Mesquites	Sept. 1943-Oct. 1944	--	39.6[b]
CALIFORNIA				
Santa Ana	Saltgrass	May 1929-Apr. 1932	12	42.7[c]
Santa Ana	Saltgrass	May 1929-Apr. 1932	24	35.3[c]
Santa Ana	Saltgrass	May 1929-Apr. 1932	36	23.8[c]
Santa Ana	Saltgrass	May 1929-Apr. 1932	48	13.4[c]
Santa Ana	Willows	May 1930-Apr. 1931	24	45.0[c]
Victorville	Tules	Jan. 1931-Dec. 1932	0	78.4[c]
San Luis Rey	Tules	Jan. 1940-Dec. 1943	0	58.9[d]
San Luis Rey	Cottonwoods[a]	Apr. 1941-Mar. 1943	48	62.5[d]
San Luis Rey	Cottonwoods[a]	Apr. 1939-Mar. 1941	36	91.5[d]
NEW MEXICO				
Carlsbad	Saltcedar	Jan. 1940-Dec. 1940	36	57.3[e,f]
Carlsbad	Sacaton	Jan. 1940-Dec. 1940	24	48.1[e]
Carlsbad	Saltcedar	Jan. 1940-Dec. 1940	24	62.9[e,f]

[a] 100% volume density. [b] "Used Water by Bottom-Land Vegetation in Lower Safford Valley, Ariz.," by J. S. Gatewood, W. T. Robinson, et al., Water Supply Paper 1103, U. S. Geol. Survey, Dept. of the Interior, 1950. [c] "Water Losses Under Natural Conditions from Wet Areas in Southern California," by Harry F. Blaney, C. A. Taylor, and Arthur A. Young, Bulletin No. 44, Calif. State Dept. Pub. Works, Div. of Water Resources, 1933. [d] "Utilization of the Waters of the Lower San Luis Rey Valley, San Diego County, California," by Dean C. Muckel and Harry F. Blaney, U. S. Dept. of Agric., 1945. [e] "Consumptive Water Use and Requirements, Report of the Participating Agencies, Pecos River Joint Investigation," by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle, Natl. Resources Planning Bd., 1942. [f] 80% density.

basins is the Blaney-Criddle method.[9] Measured consumptive use of water, by months, is related to mean monthly temperature and percentage of daytime hours to develop consumptive use coefficients. These coefficients are then applied to monthly temperature and daytime hour data for other areas to obtain estimates of consumptive use. This method has been used to estimate rates of

[9] "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data," by Harry F. Blaney and Wayne D. Criddle, SCS-TP-96, U. S. Dept. of Agric., Washington, D. C., August, 1950.

use in the Upper Colorado River, Lower Colorado River, Upper Rio Grande and California river basins, and the San Francisco Bay area.

Studies have indicated[10] that observed evaporation data from Weather Bureau, United States Dept. of Commerce (USWB), pans may be used as a means of estimating evapotranspiration by water-loving vegetation when the relation of the two values is known for a particular area. This was accomplished for the Pecos River Basin, New Mexico and Texas, in the Pecos River Joint Investigations,[11] as illustrated in Table 2.

PHREATOPHYTE PROBLEM AREAS

The phreatophyte problem is present in many western river basins. However, it is more acute in the Colorado River, Gila River, Rio Grande, and

TABLE 2.—AVERAGE COMPUTED RATES OF ANNUAL CONSUMPTIVE USE BY PHREATOPHYTES

Location	Computed consumptive use of water, in inches			
	Saltcedar along river	Satcedar average	Brush areas away from river	Grass and weeds away from river
(1)	(2)	(3)	(4)	(5)
New Mexico				
Las Vegas	51.6	43.2	34.8	21.6
Fort Sumner	64.8	51.6	43.2	27.6
Roswell	67.4	56.4	45.6	28.8
Carlsbad	72.0	60.0	48.0	30.0
Texas				
Barstow	71.8	58.8	46.8	30.0
Balmorhea	72.0	60.0	48.0	30.0
Fort Stockton	72.0	60.0	48.0	30.0

Pecos River basins. Dense growth, particularly saltcedar, is causing accumulations of sediment, blocking river channels, and thereby reducing their water-carrying capacity and creating flood hazards. W. T. Robinson, of the U.S.G.S., has prepared a map showing the distribution of phreatophytes in the Western United States. It has been estimated that the total area of phreatophytes covers more than 16 million acres of land in the 17 Western States and discharges as much as 25 million acre-ft of water evapotranspiration into the atmosphere annually, which is about twice the mean flow of the Lower Colorado River.[12]

10 "Relationship of Pan Evaporation to Evapo-transpiration by Phreatophytes and Hydrophytes," by Harry F. Blaney, Western Soil and Water Management Research Soil and Water Conserv. Research Div., U. S. Dept. of Agric., and Phreatophyte SubCommittee, PSIAC, 1958.

11 "Consumptive Water Use and Requirements, Report of the Participating Agencies, Pecos River Joint Investigation," by Harry F. Blaney, Paul A. Ewing, Karl V. Morin, and Wayne D. Criddle, Natl. Resources Planning Bd., 1942.

12 "Phreatophytes," by W. T. Robinson, U.S.G.S., U. S. Dept. of the Interior, Denver, Colo., Water Supply Paper No. 1423, 1958.

This water is equivalent to about ten times the storage capacity of the Elephant Butte Reservoir on the Upper Rio Grande in New Mexico.

According to Committee Report No. 21[13] of the Select Committee on National Water Resources, United States:

> "The Bureau of Reclamation estimates the stream depletion of the main stem of the Colorado River below Lee Ferry as nearly 600,000 acre-feet a year and for the entire basin below Lee Ferry at about twice this amount."

The area of phreatophytes in the states of Arizona, California, New Mexico, Nevada, Utah, and Colorado based on the most recent data, is estimated as 7 million acres, and the water consumed by the plants from 10 million acre ft per yr to 12 million acre-ft per yr. For the states of Arizona and New Mexico, the estimated area is a little less than 1 million acres and the estimated annual water use is between 2-1/2 million acre-ft and 3 million acre-ft.

Saltcedar is the major problem phreatophyte in the Southwest. It is vigorous, agressive, spreads rapidly, and is very difficult to eradicate. This is illustrated by the rapid increase of saltcedar in New Mexico, although control measures have been underway for about 10 yr. Surveys indicate that on the Pecos River, from Alamogordo Dam, New Mex., to Texas Line, this plant growth has increased from zero in 1912, to 15,000 acres in 1939, and to over 50,000 acres in 1960. On the Upper Rio Grande, from Bernardo to San Marcial in New Mexico, the infestation has ranged from zero in 1914 to 65,000 acres in 1960.

CONSERVATION OF WATER LOSSES

Conservation of water by eradication or control of phreatophytes is very difficult and expensive. Although cottonwoods have been controlled in several acres, economic methods for eradication of saltcedar have not been developed. Conservation, or salvage of water used by phreatophytic vegetation, may be effected by (a) lowering the water table below root zone by pumping or drainage, (b) chemical or mechanical controls, (c) replacement with plants of high economic value, and (d) management practices that will maintain desirable plants. The degree of salvage will depend on the value of replacement vegetation.

Although the water consumed by phreatophytes is available for salvage, it may not be economically feasible to salvage all the water wasted. Also, only a portion of it would be available at points of farm use. In any program involving salvage, however, it is essential to have as much information as possible concerning the occurrence and water requirements of the plants in the area under consideration.

Studies made by Muckel and Blaney in Southern California in about 1945 indicated that 50% of the water consumed by cottonwood trees could be salvaged for irrigated crops in a closed groundwater basin. In 1951, a preliminary survey was made by the Soil Conservation Service, United States Dept. of Agriculture of about 46,000 acres of phreatophytes growing in the Rio Grande Basin between Cochiti and San Marcial. A tentative estimate indicates an average

13 "Water Resources Activities in the United States," Evapo-transpiration Reduction, No. 21, Select Committee on Natl. Resources, U. S. Senate, 1960.

rate of consumptive use of 5 acre-ft per acre per yr. After an allowance was made for valley losses to San Marcial it was estimated that in round numbers, 90,000 acre-ft of water could be conserved annually by control of the phreatophytes.

Based on area and density data shown in the Thompson report,[14] and measured consumptive use by phreatophytes in the Pecos River Valley, Table 3 shows the amount of water that might be saved under a control program for saltcedar. This amounts to about 49%.

S. F. Cramer, F. ASCE,[15] recommended that about 94 miles of the Gila River channel, from the head of Safford Valley to Buttes Damsite, Ariz., be cleared of phreatophytes. This clearing would mechanically remove about 14,300 acres of phreatophytes. Cramer estimated by the Blaney-Criddle formula that the annual consumptive use by various types of vegetation to be cleared was about 48,000 acre-ft, and that the water consumption by replacement grasses would be approximately 12,000 acre-ft per year. From this net saving of 36,000 acre-ft annually, it was estimated that about 20,000 acre-ft would become available for irrigation at points of farm use. The economic value of salvaged water delivered to the farm was estimated at about $9.00 per acre-ft.

Present cost of eradicating phreatophytes varies widely depending on the species and density of plants and methods used. However, the land cleared must be put to some agricultural use, or another method of control used to prevent regrowth.

A cooperative investigation in the Welton-Mohawk area of the Lower Gila River[16] conducted by the University of Arizona, Tucson, Ariz., from 1958 to 1960, indicated that the cost of clearing saltcedar by undercutting ranged from $6.00 per acre to $30.00 per acre, and that the cost per acre for raking and stacking saltcedar brush ranged from $7.00 to $16.00. The cost of burning the brush piles was very insignificant compared with the over-all cost of clearing.

SUMMARY

Water losses by phreatophytes are most acute in areas in which water supplies are limited. It is estimated these water-loving plants consume nearly 25 million acre-ft annually in the Western United States. Measurements of consumptive use and estimates of consumptive waste that might be salvaged for beneficial use have been presented.

CONCLUSIONS AND RECOMMENDATIONS

For many years scattered measurements of consumptive use by phreatophytes have been made in several areas, but there are no long-term records.

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14 "Importance of Phreatophytes in Water Supply," by C. B. Thompson, Proceedings, ASCE, Vol. 84, No. IR 1, January, 1958.

15 "Salvage of Water by Controlling Phreatophytes," by S. F. Cramer, U. S. Army Corps of Engrs., Irrig. and Drainage Session; presented at the April, 1961 ASCE Convention at Phoenix, Ariz.

16 "Report on the Wellton-Mohawk Saltcedar Clearing Studies," by K. R. Frost, Jr. and K. C. Hamilton, Report No. 193, Univ. of Arizona, Tucson, Ariz., November, 1960.

TABLE 3.—ESTIMATED AMOUNT OF WATER THAT MIGHT BE SAVED BY REPLACING SALTCEDAR WITH BERMUDA GRASS ALONG PORTIONS OF PECOS RIVER, NEW MEX.

Location	Density	Area, Acres	Consumptive Use of Water				Annual savings (salvage)		
			Without control[a]		With control[b]				
			Acre-feet per acre	Acre-feet	Acre-feet per acre	Acre-feet	Acre-feet	Acre-feet per acre	Percentage[c]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Alamogordo Dam to Acme Gage	light	6,785	3.5	23,700	2.0	12,570	11,130	1.64	
	med.	1,130	4.5	5,080	2.0	2,260	2,820	2.50	
	dense	-	-	-	-	-	-	-	
	Subtotal	7,915		28,780		14,830	13,950		49
Acme Gage to Artesia Gage	light	5,800	3.5	20,120	2.0	11,600	8,520	1.47	
	med.	3,020	4.7	14,300	2.0	6,040	8,260	2.73	
	dense	1,515	5.5	8,350	3.0	4,545	3,805	2.51	
	Subtotal	10,335		42,770		22,185	20,585		48
Artesia Gage to Carlsbad Gage	light	880	4.0	3,520	2.0	1,760	1,760	2.00	
	med.	5,400	5.0	27,000	2.5	13,500	13,500	2.50	
	dense	5,780	6.0	34,680	3.0	17,340	17,340	3.00	
	Subtotal	12,060		65,200		32,600	32,600		50
	Total	30,310		136,750		69,615	67,135		49

[a] Saltcedar [b] Replacement vegetation (Bermuda or other grass). [c] Average

These plants are spreading rapidly and depleting the water supply for irrigation from Western rivers and streams.

New research studies should be so planned as to permit determination of (1) water losses caused by phreatophytes (such as saltcedars and cottonwoods), (2) improved methods to control or eliminate undesirable phreatophytes, (3) amount of water losses that can be salvaged, and (4) improved management practices for phreatophytic areas.

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THE SOIL DRAINABILITY FACTOR IN LAND CLASSIFICATION

By Claude L. Fly[1]

SYNOPSIS

Considerable progress has been made in deriving usable soil drainability formulae from physical characteristics which are identifiable and measurable. However, the classification of land as to its use capability before and after drainage has commonly been based on loosely descriptive terms subject to local variations in interpretation. The major factors affecting agricultural drainage are listed and their relation to land classification explained. A summation of the physical, agronomic and economic components indicate only two: hydraulic conductivity and character of the aquifer zone and depth to limiting layers, as physically measurable and sufficiently constant to form a basis for drainability classification.

Based on considerable experience in determining the relation of drainability to use capability of land for irrigation purposes, a set of drainability class limit curves have been computed. These curves coincide with the agronomic limits of land capability classes as used by the Soil Conservation Service, U. S. Department of Agriculture.

From these a tentative soil drainability rating guide for evaluating lands for irrigation use is presented. The effect of economic levels and acceptable agronomic practices on the limiting curves for drainability classes is exam-

Note.—Discussion open until February 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. IR 3, September, 1961.

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ined. This drainability rating method provides a useful approach to classification of soil drainability for irrigated lands.

INTRODUCTION

A number of the concepts presented herein were developed during the soils and drainage investigations of large land tracts for irrigation development in southwestern Afghanistan. While the techniques employed in these surveys and studies followed closely those used by federal and state agencies in the United States, certain adaptations in the concepts of data evaluation and interpretation were found effective.

Considerable progress has been made to define soil drainability in physically measurable and identifiable values, capable of practical mathematical solution (1).[2] Such values, used in association with other basic land factors, enable more accurate classification of land use capability (12).

Land Use Capability Classification.—This concept, as it is commonly used in the United States, has essentially agronomic (plant growth) units bounded by relative degrees of use limitations or hazards of use and feasibility of land treatment. These limits are subject to some variation based on local experience in agricultural land usage.

The agronomic requirements of each succeeding land class shift from a set of environmental factors (soil, climate, drainage, and so on) favorable to the widest choice of crops and agronomic practices (Class I) toward narrower choices until a condition unsuitable for agricultural usage (Class VIII) is reached. Each succeeding class, therefore, involves increasingly narrower use capability within which the specific limits of physical factors (soil properties, slope, land drainability, and so on) are locally defined. For example, the depth to impermeable layers, the aquifer conductivity and its stratification and thickness, and the character of the drainage outlet of a given site may combine to produce, along with other factors, an environment for plant growth equivalent to that accepted as "Class II" land. For "Class IV" land, these factors would likely be much more restrictive for plant growth.

Within a prescribed locale, experience and custom lead to acceptance of certain land use levels circumscribed by certain degrees of hazards or limitations to use and to feasibility of land treatment. In another locale, the accepted levels of land use and "feasibility" may be different, so that, within the more or less loosely defined hazards and limitations that form a land capability class, the specific measurable limits of drainability and other physical factors affecting plant environment shift relative to the prevailing agricultural customs, agricultural economy, and thought pattern of the locale. While a great deal of progress has been made toward uniformity, the measurable combinations of soil, climate, and other associated environmental properties have not (as of 1961) been adequately described for an acceptable world-wide land classification.

Agronomic Customs Vary with Respect to Drainage.—In attempting to use the land capability class concept in other countries, in climatic situations ranging from humid tropical to arid temperature, the writer encountered a variety

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[2] Numerals in parenthese refer to corresponding items in the Appendix.

of situations. Soil drainability is illustrative of this variation in local land use. Soil drainability as used refers to the total movement of water under gravitational influence through the solum and substratum and its effect on the root zone environment for crops. In Ceylon[3] and Siam, rice, a staple crop, is produced on fine-textured, slowly permeable soils having no drainable substrata (3). Only surface drainage is used. Tea, another very valuable crop is produced on high, steep, mountain slopes having rapidly drainable soils. Very poor drainability was a cost factor in the extensive development of the Pontine marshes in Italy, but was not prohibitive of land development. In Greece, some clay valley soils are waterlogged and producing only coarse grasses, while rapidly drainable soils benched with stone walls on 80% slopes are producing wheat and corn (4). In Afghanistan, narrow strips of winter wheat are grown in the midst of large tracts of extremely saline-alkali desert soils of very poor drainability.[4] Some of the more drainable soils have been waterlogged and salinized by poor irrigation practices. The tidal salt marshes, diked off by the Dutch in the great Zuiderzee projects, are being reclaimed to agricultural use. Although the degree of use depends on the water table level and soil permeability, few lands are wasted. In some areas, almost pure sands are subirrigated, as are some peat soils (both of very rapid drainability) to produce profitable crops.

SOIL DRAINABILITY

Constant and Measurable Components.—In the use of soil drainability in land classification there is a need for physically measurable components expressed in units capable of mathematical solution (5). These generally constant and primary determining factors of drainability were found to be hydraulic conductivity of the aquifer zone and depth to barriers. "Hydraulic conductivity," as used herein, means the mass effect of the combined lateral and vertical conductance of water through the soil and substrata material to an outlet drain. Barriers are impervious strata that tend to perch water tables sufficiently long to seriously injure plant roots. The presence of indurated materials at shallow depths may create cost problems affecting feasibility of drainage but may or may not result in perched water tables.

Drainage Components Subject to Arbitrary Adjustment.—Most other drainage factors of importance can be described in terms of the root growth environment required for a given crop or sequence of crops.

Water Removal Rate.—The expected volume of drain water to be removed varies according to intensity, and duration of rainfall or the efficiency of application of irrigation water but, except for special conditions, cannot be less than the leaching requirement for maintenance of a salt balance that is tolerated by the crops to be grown. The leaching requirement can be computed from the electrical conductivity of the irrigation and drainage waters and the consumptive use requirement of the crop (6).

Irrigation Efficiency.—The efficiency of water application is dependent upon a number of variables, including an indeterminate human factor. Soil infiltra-

[3] "Agricultural Potentials of the Walawe Gange Watershed, Ceylon," by C. L. Fly, Internatl. Engrg. Co., 1954. (Obtainable by permission only).

[4] "Soil and Water Resources of Southwest Afghanistan," by C. L. Fly, Internatl. Engrg. Co., 1958. (Obtainable by permission only).

tion characteristics and soil depth and moisture storage capacity determine practical amounts of irrigation application when considered together with the consumptive use requirements of the crop. The quality of the irrigation layout (degree of leveling and ratio of length of runs and widths of borders to irrigation head) and percolation losses in the distribution system both affect the quantity of water that must be removed by drainage. The indeterminate human element enters into the efficiency of water application. Measurements evaluating efficiency by trial runs can be made and relative or arbitrary values assumed. Irrigation efficiency is one of the components of the drainage problem that is subject to constant improvement but which, commonly, is a fluctuating or assumed value.

Drain Placement.—The depth, slope, and often the type of drains are determined by depth and thickness of suitable aquifers, depth to barriers, and the elevation and accessibility of outlet drains. Within the limits imposed by these conditions, some choice is possible depending on the crops to be grown and the relative costs involved. The spacing of drains, which is a primary cost factor, depends upon the range of choice available. The comparative benefit—cost ratio of the different drainage schemes and their potential crop growth levels, form a basis for selecting the system as well as the crops that can be successfully grown after the system is in operation. In some cases, rather wide choices may exist. In others, limited choices exist. Spacing can be determined for any given set of specified conditions.

Drainage Costs.—The cost of drainage of a given site situation may be varied by choice of crops with different root zone requirements and tolerance to high water tables and salinity (9). For instance, certain nut and fruit trees require 5 ft to 6 ft of well-drained soil, and soil solution concentrations below 3 mhos per cm conductance (7). Salt-tolerant grass-legume pastures may tolerate saline soil solutions having as high as 16 mhos per cm conductance and may grow well on 1 ft of drained soil (1). Labor, equipment, and material costs vary widely from place to place. Only when all conditions are well known can the costs be reasonably determined. The choice of crops and the final costs would be affected by the demand and the market value of these crops in the local area. A shifting economy could change the entire picture and favor or discourage a given level of drainage. For these reasons, cost is a factor which, within certain physical limits, can fluctuate widely.

Drainage Feasibility.—Feasibility of drainage is generally associated with a favorable ratio of output (production) to input (costs) and should well be so where the profit motive is the reason for drainage. Generally, this type of appraisal is made if private enterprise undertakes drainage and assumes the costs and risks involved. If population pressure within a country is the major reason for drainage (Pontine marshes of Italy; Zuiderzee of Holland), the immediate profit motive may not be used as a yardstick because greater costs and risks may be assumed as a national obligation. The resettlement of people, resulting in new homes, towns, industries, and work opportunities, relieves the congestion and pressure on older lands so that the national benefits (output) eventually equal or exceed the national expenditures (input) for the project. In other situations, political expediency may dictate the development of an area in order to establish prior use rights to water or land resources. Feasibility of drainage, then, is a variable factor, except where the profit motive is the only consideration and all conditions are known and specified.

In summation, only two of the various physical, agronomic, and economic components of soil drainage appear reasonably constant and measurable for irrigated lands. All other factors involve choices, assumptions, or specified conditions that may vary from locale to locale or with time. Also, in humid areas, freezing, thawing, biological activity and tillage may affect marked changes in hydraulic conductivity of the upper soil layers.

DEVELOPMENT OF A DRAINABILITY CLASSIFICATION

Preliminary Drainability Classification.—Field determination of hydraulic conductivity of aquifers and depths to impermeable strata (barriers) is the

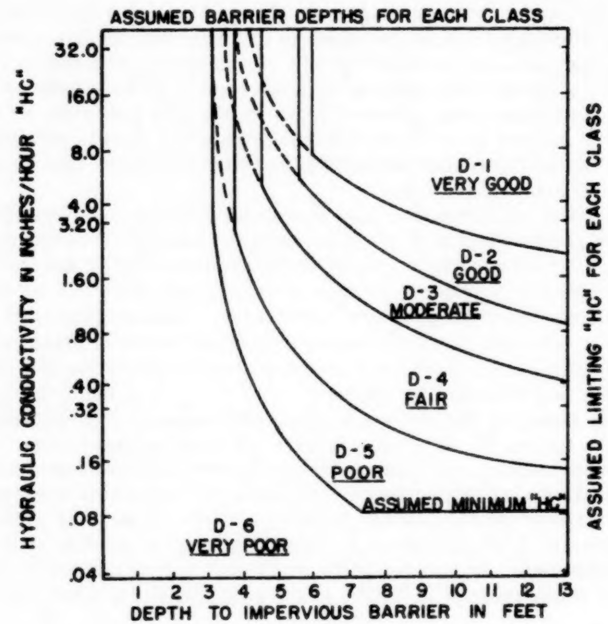

FIG. 1.—DRAINABILITY CLASSES WITH ARBITRARY LIMITS

first step toward obtaining a drainability classification. The ranges and extreme limits of hydraulic conductivity and barrier depths used would be established by data from the drainage and soil surveys of the area. Fig. 1 illustrates an arrangement of such data as used in one area for drainability class ranges. The six classes may be more or less than needed in another locale. Superimposed on this classification was another factor: Depth to hard material which is difficult or costly to excavate (shown by the vertical lines). Many areas are not affected by this particular drainage problem. The Donnan

formula (8) was used in computing the boundary curves for each drainability class:

$$S^2 = 4\ P\ \frac{(b^2 - a^2)}{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which S is the drain spacing, in feet; P denotes the weighted average hydraulic conductivity of saturated zone, in inches per hour; b refers to the depth of water table, in feet, over a barrier and midway between drain lines; a is the depth of water over barrier in center of drain, in feet; and Q refers to the required drainage removal, in cubic feet per second per acre.

Arbitrary Limits.—The solution of the boundary curves of these six drainability classes involved assumed values of drainage yield and drawdown depths. These, in turn, fixed arbitrary limits for the minimum allowable barrier depths and hydraulic conductivity within a given class. The hydraulic conductivity was prorated by horizons from 50 cm depth to this barrier. In this case, also, the assumption that any soil horizon having a permeability less than 0.1 in. per hr is a barrier, automatically places all soils of slow to very slow permeability in the very poor class regardless of depth or any other considerations. Obviously, factors subject to arbitrary choice have a great deal to do with the range of absolute values (hydraulic conductivity and barrier depths) that may be placed within a given drainability class.

Consideration of Agronomic and Economic Factors.—Following drainage surveys, the second step is to evaluate the data in terms of agronomic significance. Each set of conditions, that is, hydraulic conductivity and barrier depth, has a given effect on producing a range of crop growth environment when treatment and management is properly considered. Because the land capability class concept involves certain commonly accepted levels of plant growth environment for each class, these have been used here to guide the selection of factor limits for soil drainability classes.

Minimum Leaching Requirement.—One advantage of this approach is that the minimum values of the drainage rate, Q, may be determined for a given climate, water supply, and crop pattern. Research has shown the minimum leaching requirement can be determined from the irrigation water quality and from the consumptive use and salt tolerance of the crops to be grown (6).

The minimum Q values shown in Table 1 are from studies made in southwestern Afghanistan. In this table, the method of computing minimum leaching of drainage requirements is based on the equation and analysis by Reeve (6):

$$Dw = \frac{ECiw}{ECdw - ECiw} \times Dcw \quad \ldots\ldots\ldots\ldots\ldots (2)$$

in which Dw denotes the drainage water required to maintain salt balance; Dcw describes the consumptive use as computed by the Blaney-Criddle method; ECdw is the conductance of drainage water, and ECiw refers to the conductance of irrigation water. The consumptive use values are those determined for these crops in the Helmand Valley of Afghanistan, using the Blaney-Criddle method (9). Tolerance levels of crops were selected from the U. S. Dept. of Agriculture (USDA) Handbook No. 60 (7); the values selected are those at about the 50% crop production level.

Where water of excellent to good quality for irrigation was available, the minimum requirement for drainage removal to maintain a satisfactory salt

TABLE 1.—MINIMUM DRAINAGE REQUIREMENTS TO MAINTAIN A SALT BALANCE TOLERATED BY CROPS IN THE HELMAND VALLEY, AFGHANISTAN

Crop (1)	Tolerance ECdw (mhos per cm) (2)	Consumptive Use Dcw Inches (3)	Arghandab Water[a] Leaching Req. Percent (4)	Minimum Q Cfs per Acre (5)	Consumptive Use Dcw (6)	Helmand Water[a] Leaching Requirement, Percentage (7)	Minimum Q Cfs per Acre (8)
Wheat	9	15	5.14	0.00035	16.2	3.42	0.00027
Alfalfa	8	48	5.82	0.00058	51.6	3.90	0.00046
Corn	6	20	7.90	0.00068	21.6	5.26	0.00052
Cotton	12	25	3.81	0.00030	27.0	2.56	0.00022
Vegetables	6	15	7.90	0.00058	16.2	5.26	0.00045
Decidious Fruits	4	30	12.35	0.00083	32.3	8.10	0.00065
Grapes	6	20	7.90	0.00049	21.6	5.26	0.00037
Potatoes	6	16	7.90	0.00064	17.2	5.26	0.00050
Nut trees	3	35	17.20	0.00132	37.7	10.00	0.00092
Salt-tolerant irrigable pasture	16	48	2.83	0.00025	51.6	1.91	0.00020

[a] Conductance of Arghandab River water was EC x 10^3 = 0.44; of Helmand River water was 0.30, approximately.

balance ranged as low as 0.0002 cfs per acre. The drainage volume required was five or six times greater for a crop of low salt tolerance. Because the amount of drain water to be removed primarily determines the number of drains that must be installed, the selection of a cropping plan can make a great deal of difference in drain spacing (10). Tables similar to Table 1 can be prepared for any local situation for which the quality of the irrigation water, the evapotranspiration requirements of plants and plant tolerance to salts are known. This procedure establishes the highest degree of efficiency that can be reached by irrigation processes without endangering the crops by increased salinization. Beyond this minimum value for drainage requirement, additional percolation losses are governed mostly by the application of irrigation techniques to obtain higher efficiencies of use. Therefore, under any given soil, climate, and crop situation the goal can be established toward which the irrigator must strive if he is to reach maximum efficiency. In common practice, it is not expected that this goal will be reached.

Other Agronomic Components of Drainage.—Having established the minimum drainage requirements and determined the nature of the soils with respect to hydraulic conductivity and barrier depths, one must consider also the limitations imposed by other factors affecting crop growth environment. Table 2 illustrates this process by assuming that these conditions prevail after development and treatment. Temporary removable water tables or salinity are not determining factors. Table 2 summarizes those definitions and land class limits commonly accepted as drainage criteria, both in the United States and in other countries in which such studies have been made. While there is inadequate research data available to establish the consistency or reliability of these interrelated factors, it is felt that, in general, they describe acceptable limitations for the various land classes.

For each factor, Table 2 describes those minimum limits that fit the agronomic concept of the several capability classes. Nontillable classes V to VIII are grouped into one for convenience. For example, a salinity level of 4 mhos per cm or less conductance in the soil solution permits growth of most crops and consequently could be an acceptable condition in a Class I soil. A recurrent salinity of 8 to 14 mhos per cm would restrict the growth of several common crops and limit the use of the soil to production of the more tolerant field crops, grasses and legumes, and would probably require periodic leaching for control of salinity under most cropping plans. Such conditions are typical of Class III land capability. Similarly, drawdown rates and depths are important in establishing proper plant root environment for successful growth. Class I soils having few or no limitations of growth for a wide choice of crops must be deep, well-drained, and have high waterholding capacity. At the other extreme, Class IV lands may be shallow, have a high, fluctuating water table, and be subject to strong salinization. These conditions are described in tabular form by classes in Table 2.

Costs and Feasibility.—Costs and the economic feasibility of drainage are, locally, major factors in determining whether an area of land will or will not be developed or improved. From the physical data on drainability and the plant environment requirements (Table 2) one can compute drain depth and spacing for the appropriate type of drains. The feasibility of drainage is a problem for local determination, however. No uniform set of standards would be acceptable over a wide area or under widely different economic situations. The requirements for establishing a given plant growth environment can

TABLE 2.—APPROXIMATE CAPABILITY CLASS LIMITS OF SOIL DRAINABILITY FACTORS

Drainage Factor (1)	Class I (2)	Class II (3)	Class III (4)	Class IV (5)	Class V - VIII (6)
Drawdown:					
Depth (water table level limiting root growth)	>5 ft.-sandy or medium soils. >6 ft. -clayey soils	>3 1/2 ft.-sandy soils >4 1/2 ft.-medium soils >5 1/2 ft.-clayey soils	>2 1/2 ft.-sandy soils >3 1/2 ft.-medium soils >4 1/2 ft.-clayey soils	>1 1/2 ft.-any soil, wetness continuous hazard	<1 1/2 ft. or permanently waterlogged
Time and Rate	5-6 ft. in 3-5 days or $\geqq$ 1 ft. per day	4 ft. in 4-5 days, or to above depths in 1/2 irrigation cycle, peak season	To above depths in 1/2 irrigation cycle peak season	Permits growth of water-tolerant legumes and grasses and occasional cultivated crops	Permanently waterlogged, only marsh plants grow
Salt Balance:					
Drainage requirement for	<10% consumptive use and quickly removable below root depth	Meets needs all moderately tolerant crops within above drawdown time	Annual leaching to permit growth of tolerant field crops	Periodic leaching to grow tolerant grasses and legumes	Salt balance cannot be maintained
Soil solution concentration	Nonrecurring salinity, or normal level $\leqq$ 4 mhos/cm.	Occasional recurring salinity, or normal level of 4-8 mhos/cm.	Recurrent, removable strong salinity, or 8-14 mhos/cm. common	Recurrent, removable very strong salinity or 12-18 mhos./cm	Nonremovable salinity prevents use for sown or tilled crops
Plant Root Environment:					
Water table fluctuations	Below plant root zone for major part of irrigation cycle	Occasionally restricts growth or choice of crops	Widely fluctuating, restricts choice crops, reduces yields	Excessive, restricts use to water-tolerant legumes and grasses	Continuously waterlogged, only marsh plants grow
Root aeration	Very good all seasons	Poor for short time after each irrigation	Fair to poor only, requires special care in irrigation and tillage	Poor and restrictive of field crops	Continuously waterlogged
Soil capacity for total readily available moisture (TRAM)	TRAM >4 in.	TRAM 3 - 4 in.	TRAM 2- 3 in.	TRAM 1 1/2 - 2 in.	TRAM < 1 1/2 in.

be determined and the costs locally computed to serve as the basis for decisions involving economic considerations (11).

Adjustment of Drainability Classes to Land Capability Class Limits.—The third major step, then, is to reconstruct the drainability classes within the concepts and limits of the land capability classes. To do so, the drainability classes must correlate with the crop growth environment prerequisite for each land class. The projection of the curves within these limits physically boundary the values of hydraulic conductivity and barrier depths acceptable for each land class. In Table 3, key values selected to establish land class limits are calculated for increasing depths to drainage barriers and for increasing hydraulic conductivity of the saturated soil zone.

Computation of Land Class Limits.—A barrier (column 1) is defined as any strata which will cause a perched water table to persist, even under careful water management, long enough to seriously harm roots of common crops. In the Afghanistan study from which Fig. 1 was computed, a barrier was assumed to be any layer, 1 ft or more in thickness, transmitting less than 0.1 in. per hr of water or having less than 10% of the hydraulic conductivity of overlying layers. The agronomic concept was used in computing Table 3 and later in the adjusted curves for Fig. 2. The "mid-tile" drawdown was assumed (column 3) to be reached at least by one-half the irrigation cycle at the peak demand period. For any given crop the computation was based on the length of time the plant roots could be submerged without serious injury. The amount of drainage water "Q" to be removed within a specified time was computed by the Reeve formula (6) in cubic feet per second per acre drained (column 4). The capacity of the soil column to provide readily available moisture (TRAM), the average daily evaportranspiration during the peak season of demand, and percolation losses computed from the soil intake rate, waterholding capacity and normal irrigation head, were used in addition to the removal time of one-half the peak irrigation cycle.

Example.—Assume TRAM = 4.0 in.; daily evaporation = 0.25 in.; percolation losses = 10%.

$$\frac{4.0\ -\ 0.4}{0.25\ \times\ 2} = 7.2\ \text{days}$$

$$\frac{4.0\ .\ 0.1}{7.2\ \times\ 24} = Q = .0023\ \text{cfs per acre}$$

Drain spacings were computed by the Donnan formula (8). Assumed minimum drain spacings for each land capability class are I = 1,320 ft; II = 150 ft; III = 75 ft; and IV = 35 ft, respectively.

Drainability Class Curves.—From data such as illustrated in Table 3, it is now possible to reconstruct the drainability class limits to correlate with those of the land capability classes. Fig. 2 shows the drainability class boundary curves adjusted to land capability class limits. While a certain bias is detected in the boundary curves due to the limits used, two important points are divulged by the application of the Donnan equation to the values in Table 3. Very careful control of irrigation water for minimum percolation losses allows the possibility of maintaining a higher crop growth environment on shallower soils over barriers, and also the possibility of maintaining suitable crop environment on soils having a much lower hydraulic conductivity than commonly accepted as standard for a land class.

TABLE 3.—COMPARISON OF DRAINAGE CHARACTERISTICS, CALCULATED DRAIN SPACING AND RELATIVE DRAINABILITY CLASS

Depth to Barrier, in feet (1)	Hydraulic Conductivity, inches per hour (2)	Mid-tile Drawdown, in feet (3)	Probable Drainage "Q" cfs per acre (4)	Calc. Drain Spacing, in feet (5)	Drainability Class (numerical) (6)	Relative Irrigation Efficiency (7)
2.5	<0.025	<1.5	0.00025+	<33	d5	
2.5	0.025	1.5	0.0002	33	d4	H[a]
2.5	1.36	1.5	0.01	33	d4	N
2.5	2.72	1.5	0.02	33	d4	L
4.264	<0.004	1.5	>0.0002	<33	d5	H
4.264	0.75	1.5	0.02	33	d4	L
4.264	7.88	3.0	0.0075	80	d3	N
4.264	31.80	3.0	0.02	100	d3	L
4.92	<0.005	1.5	>0.0002	<33	d5	H
4.92	0.885	1.5	0.01	62	d4	N
4.92	3.54	3.0	0.0075	77	d3	N
4.92	14.15	3.5	0.0075	115	d3	N
4.92	31.80	3.5	0.0075	175	d2	H
4.92	31.80	3.5	0.02	108	d3	L
6.56	<0.002	1.5	>0.0002	<33	d4	H
6.56	0.155	1.5	0.0075	45	d4	N
6.56	0.59	3.5	0.0025	90	d3	H
6.56	2.38	3.5	0.0075	108	d3	N
6.56	5.12	3.5	0.0075	157	d2	N
6.56	>100.00	5.0	<0.0005	>1320	d1	H
8.2	<0.001	1.5	0.0002	<33	d5	H
8.2	0.10	1.5	0.0075	50	d4	N
8.2	0.31	3.5	0.0025	105	d3	H
8.2	1.24	3.5	0.0075	120	d3	N
8.2	2.75	3.5	0.01	155	d2	N
8.2	<327.0	5.0	>0.0075	<1320	d2	N
8.2	>22.0	5.0	<0.0005	>1320	d1	H
9.84	<0.0008	1.5	>0.0002	<33	d5	H
9.84	0.03	1.5	0.0075	33	d4	N
9.84	0.158	4.5	0.0025	105	d3	H
9.84	0.77	3.5	0.0075	130	d3	N
9.84	1.73	3.5	0.0075	195	d2	N
9.84	>10.0	5.0	<0.0005	>1320	d1	H
11.48	<0.0006	1.5	>0.0002	<33	d5	H
11.48	0.02	1.5	0.0075	33	d4	N
11.48	0.138	4.5	0.0025	90	d3	H
11.48	0.56	4.5	0.0075	105	d3	N
11.48	1.75	4.5	0.0075	200	d2	N
11.48	>8.7	6.0	<0.0005	>1320	d1	H
14.00	<0.00004	1.5	>0.0002	<33	d5	H
14.00	0.16	1.5	0.0075	33	d4	N
14.00	0.10	4.5	0.00025	100	d3	H
14.00	>0.88	5.5	0.0075	>150	d2	N
14.00	>5.6	6.0	<0.0005	>1320	d1	H

[a] H = high; N = normal; L = low efficiency.

Supporting Agronomic Experience.—Some experience data tend to bear out this concept. For instance, in Imperial Valley, California, farmers have found that a land Class III cropping program can be carried out on lands having very poor drainability (hydraulic conductivity ratings to a depth of 9 ft of less than 0.02 in. per hr). Near Los Banos, California, very good irrigated grass-legume pastures are being grown on saline-alkali clay soils with no subsurface drainage (12). Carefully controlled application of water is made onto leveled borders provided with adequate drains for surface removal of waste water. At the Huntley, Montana, Experiment Station (13), saline-alkali clay soils were reclaimed to grass-legume crops even though the continuous rate of water intake was less than 1 in. per day. Thus, extremely slowly permeable soils may be more of an irrigation and soil management problem than a drainage problem. Some experiments in the Soviet Union indicate that very slowly permeable, highly saline-alkali clay soils were reclaimed by a combination of mole drains, 15 in. to 24 in. deep and 15 in. to 18 in. apart, emptying into moderately shallow surface drains (14). The recent introduction of plastic drains which can be laid by machinery at shallow depths could extend drainage feasibility beyond the concepts that are outlined in Table 3 and Fig. 2.

A DRAINABILITY RATING GUIDE

After drainability classes and class limits have been determined for a given location, research and farm experience must test these limits under various situations to improve not only the drainability classes and the class limits, but the agronomic concepts under which these were first construed. When the type, depth and spacing of drains has been determined, there will remain, of course, the determination of costs and, beyond that, the determination of feasibility. All of these are local situations affected by the local concepts of the specific land class limits. Under one set of conditions of cropping patterns and local economy, it is quite possible that very little in the way of artificial drainage could be considered economical. Under another set of conditions, such as specialty crops of high value, extreme measures to obtain suitable drainage might be undertaken and the costs might be comparatively high.

As pointed out earlier, economics might be completely modified in an area where population pressure demands the development of every acre of available land. Similarly, political expediency might dictate the development of an area to establish prior-use rights to water or to land resources. Economic feasibility, in this latter case, would become a less important factor. Only where the profit motive is the primary consideration for a stable period of time, can true economic feasibility of drainage be definitely measurable.

Proposed Soil Drainability Rating Guide.—From the foregoing studies, a soil drainability rating guide has been developed to fit natural ranges of drainability to land capability classes (Table 4). The major factors affecting soil drainability are evaluated in somewhat the same manner as the Storie index for soils. In addition to the 1) barrier depth and 2) hydraulic conductivity of the aquifer, 3) stratification and 4) aquifer thickness, continuity, and location are given numerical values.

Drainability Rating Summary.—By giving a percentage value to each of five natural ranges of conditions for each factor, a method of approximating land class levels as indicated in the drainability rating summary at the bottom of

TABLE 4.—SOIL DRAINABILITY RATING GUIDE FOR EVALUATING LANDS FOR IRRIGATION USE

Factor (1)	Rating: Descriptive (2)	Rating: Percentage (3)	Factor Variations and Limits (4)
Depth to Barriers	Very good	100	None, open downwards
	Good	90	Below 10 feet
	Fair	70	5 - 10 feet
	Poor	50	2.5 - 5 feet
	Very poor[a]	30	2.5 feet
Hydraulic Conductivity of Aquifer ("HC")	Very good	100	Very rapid: >10 in./hr.
	Good	90	Rapid: 0.8 - 10 in./hr.
	Fair	70	Moderate: 0.1 - 0.8 in./hr.
	Poor	40	Poor: 0.04 - 0.1 in./hr.
	Very poor[a]	30	Very poor: <0.04 in./hr.
Stratification (layers of varying hydraulic conductivity in aquifer zone)	Very good	100	Permeability increases downward, no restrictions
	Good	90	Thin, discontinuous, slightly limiting
	Fair	80	Moderate variations in "HC" of strata, moderately limiting
	Poor	70	Wide variations in "HC" in, and below, 3-5 foot depth, poor "HC" dominating
	Very poor[a]	50	Extreme variations in "HC" at 3 feet or less, very poor "HC" dominating
Aquifer thickness, continuity and location	Very good	100	6-10 feet thick, below 5-10 feet deep and continuous
	Good	90	3-6 feet thick, 3-10 feet below surface and continuous
	Fair	70	1.5 - 3 feet thick, below 3-6 feet, semicontinuous
	Poor	50	<1.5 feet thick, <3 feet deep, discontinuous
	Very poor[a]	10	No apparent aquifer

(Product of preceding 4 factors)

Descriptive Terms (1)	Approximate Land Class Level (2)	Range of Percentage (3)	Minimum Aquifer Hydraul. Conductivity (4)
Very good	I	71 - 100	>6.0 in./hr.
Good	II	36 - 70	>0.8 in./hr.
Fair	III	15 - 35	>0.1 in./hr.
Poor	IV	3+ - 14	>0.04 in./hr.
Very poor	V-VIII	3 or less	<0.04 in./hr.

[a] If any one of the four factors is classed as "very poor," extreme care should be exercised in making drainage or land use recommendations.

the table. Here the product of the percentage ratings for the four factors ranging between 71% and 100% would be indicated as Very Good or within the land Class I level; 36% to 70% as Good—Class II level; 15% to 35% as Fair—Class III level; 3% to 14% as Poor—Class IV level; and 3% or less as Very Poor—Class V level. The minimum aquifer hydraulic conductivity inserted as column 4 in the

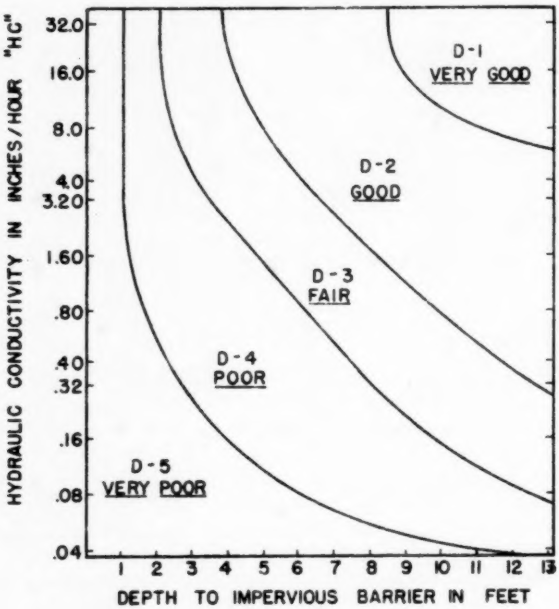

FIG. 2.—BOUNDARY CURVES OF DRAINABILITY CLASSES ADJUSTED FOR SOILS, CROPS AND LEACHING REQUIREMENTS OF LAND CAPABILITY CLASSES

Drainability Rating Summary was selected after due consideration of all agronomic and physical factors involved.

CONCLUSIONS

Several concepts of soil drainability as related to use capability of land were developed during the process of investigating and evaluating for irrigation development the soils and drainage characteristics of large land tracts in southwestern Afghanistan.

When the several components of land drainage were related to land use and irrigated land classification, two fairly constant and mathematically measurable factors were determined to be the more usable criteria of drainability. (1) Hydraulic conductivity and character of the saturated zone, and (2) the

depth to very slowly permeable or impervious strata which act as barriers to the removal of groundwater. Most other drainage components are modifiable in one way or another by economic considerations, agronomic practices, or other influences, so that they do not remain constant and measurable except under arbitrarily defined limitations. A drainability rating method, based on hydraulic conductivity and barrier depths, was developed and successfully used in a major project development. It appears to be a useful concept around which to develop drainability rating guides for use in land classification of irrigated areas, or areas selected for development. Further study may show some adaptation to other types of drainage problems. It is recognized that many of the factor limits based on current agronomic knowledge may be subject to change. Drain spacing formulae, used in 1961, are also subject to modifications as research progresses on the physical situations to which they are applied. Further research is needed to advance knowledge of the interrelationships of the various involved factors.

ACKNOWLEDGMENT

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FACTORS AFFECTING THE SAFE YIELD OF GROUND-WATER BASINS

By John F. Mann, Jr.,[1] Aff. ASCE

SYNOPSIS

The origin of the term "safe yield" is presented as are the current definitions and concepts. Ways of avoiding misunderstanding and confusion, especially in litigation, are suggested. Safe-yield determinations are studied with reference to (a) water supply available to the basin; (b) economic factors; (c) quality factors; and (d) legal factors.

INTRODUCTION

Safe yield and overdraft are problems of an advanced technologic age. Even as late as the turn of the twentieth century there was probably no such thing as an overdrafted ground-water basin. As of 1900, water production was dominated by gravity developments. Nature decided how much water the ground-water basin would spill into the gravity collection devices. Pumping of ground water was limited in volume, and by present-day standards, inefficient. Deep-well plunger pumps were installed in many small-diameter wells and lifted small quantities of water for domestic and stock use. For suction lifts and larger capacities, centrifugal and reciprocating pumps were used. As water tables dropped, centrifugal pumps in large-diameter shafts were laboriously installed on deeper and deeper platforms. For larger capacities and higher lifts, air-lift pumps were utilized, but these were notoriously inefficient. It might also be suggested that as of 1900 the technology was incapable of developing the full

Note.—Discussion open until February 1, 1962. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation Division, Proceedings of the American Society of Civil Engineers, Vol. 87, No. IR3, September, 1961.

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safe yield of ground-water basins. By 1910, however, the vertical turbine pump had been invented. With this forward step there was acquired a device which permitted the development of full safe yield, but along with it, an invitation to overdraft.

An attempt will be made to analyze various definitions and concepts of safe yield and to present those factors which must be considered if safe yield is not to be exceeded. A more general outline of the items involved in determining safe yield was given previously.[2]

Approaches to safe-yield problems have a strong climatic flavor; this paper accordingly is strongly influenced by a dry-climate hydrologic regimen. Furthermore, many of the comments are more applicable to ground-water basins of the "reservoir" type than of the "pipeline" type.

DEFINITIONS

The term "safe yield" was coined by Oscar E. Meinzer and apparently first used (but not defined) by him in 1920[3] and was used again and defined in 1923.[4]

> "The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is harmful to the aquifer itself, or to the quality of the water, or is no longer economically feasible."

Meinzer's definition has been accepted as the basis for the standard definition;[5] however, the standard definition does not include the phrase "for human use."

Another commonly quoted definition is that of Harold Conkling:[6]

> "Safe yield is the annual extraction from the ground-water unit which will not, or does not—
>
> 1. Exceed the average annual recharge;
> 2. So lower the water table that permissible cost of pumping is exceeded; or
> 3. So lower the water table as to permit intrusion of water of undesirable quality."

Important modifications in Conkling's definition were made by Harvey O. Banks,[7] F. ASCE:

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2 "Safe Yield Changes in Ground-Water Basins," by John F. Mann, Jr., Internatl. Geol. Congress, XXI Session, (Copenhagen), 1960, Part XX, p. 17.

3 "Quantitative Methods of Estimating Ground-Water Supplies," by Oscar E. Meinzer, Bulletin, Geol. Soc. of America, Vol. 31, 1920, p. 329.

4 "Outline of Ground-Water Hydrology with Definitions," by Oscar E. Meinzer, U. S. Geol. Survey, Water Supply Paper No. 494, 1923.

5 "Glossary of Geology and Related Sciences," Amer. Geol. Inst., 1957, p. 325.

6 "Utilization of Ground-Water Storage in Stream System Development," by Harold Conkling, Transactions, ASCE, Vol. 111, 1946, p. 275.

7 "Utilization of Underground Storage Reservoirs," by Harvey O. Banks, Transactions, ASCE, Vol. 118, 1953, p. 220.

"Safe yield may be defined as the average annual rate of extraction from a ground-water basin which will not:

a. Exceed the difference between the average annual supply to the waste water table as defined previously and the average annual disposal from the water table by underflow, effluent seepage, drainage, and direct consumptive use;

b. Lower the water table sufficiently to permit intrusion of sea water or other water of undesirable quality or to prevent sufficient flow through the basin to maintain proper balance of dissolved salts;

c. Lower the water table beyond the economic limit for cost of pumping; or

d. Interfere with prior rights of others in adjacent ground-water basins."

Following the definition of Banks, David K. Todd,[8] M. ASCE, has studied safe yield as generally viewed in California. Todd's broad definition is:

"Safe yield of a ground-water basin is the amount of water which can be withdrawn from it annually without producing an undesired result."

The undesired results are then presented in four categories:

1. Water supply available to the basin;
2. Economics of pumpage from the basin;
3. Quality of the ground water; and
4. Water rights in and near the basin.

Considerable dissatisfaction with the term "safe yield" has been expressed. Perhaps the most outspoken in this regard has been R. G. Kazmann,[9] F. ASCE. Harold E. Thomas[10] also expresses a lack of confidence in the term:

"Safe yield is an Alice-in-Wonderland term which means whatever its user chooses."

While perhaps not officially suggesting that the term "safe yield" be abandoned, several members of the United States Geographical Survey seem to prefer other terms to express the same concept. McGuinness[11] doesn't refer to "safe yield" but apparently uses "sustained yield" in the same sense. Gerald G. Parker[12] expresses dissatisfaction with "safe yield" and clearly prefers "perennial yield." C. C. Williams and S. W. Lohman[13] define "perennial yield" but

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8 "Ground Water Hydrology," by David K. Todd, John Wiley and Sons, New York, 1959, p. 336.

9 "'Safe Yield' in Ground-Water Development, Reality of Illusion," by R. G. Kazmann, Proceedings, ASCE, Vol. 82, No. IR3, 1956, p. 12.

10 "The Conservation of Ground Water," by Harold E. Thomas, McGraw-Hill Co., New York, 1951, p. 327.

11 "The Water Situation in the United States with Special Reference to Ground Water," by C. L. McGuinness, U. S. Geol. Survey Circular No. 114, 1951.

12 "Geologic and Hydrologic Factors in the Perennial Yield of the Biscayne Aquifer," by Gerald G. Parker, Journal, Amer. Water Works Assn., Vol. 43, 1951, p. 817.

13 "Geology and Ground-Water Resources of a Part of South-Central Kansas," by C. C. Williams and S. W. Lohman, Kansas Geol. Survey, Bulletin No. 79, 1949.

use this term interchangeably with "safe yield." Kazmann[9] expresses a preference for "perennial yield." Certainly, few would deny the term "safe yield" is something less than satisfactory. Especially in litigation, the connotation that extractions beyond a certain annual rate will result in a condition which is unsafe unduly dramatizes the situation. From this standpoint, a more innocuous expression such as "sustained yield" or "perennial yield" is preferable.

But apart from matters of terminology, there is the unquestioned necessity of deriving a quantitative estimate of the amounts of water which can be extracted from a ground-water basin without causing eventual difficulties. If ground-water basins are to be managed efficiently, some such figure must be derived, even though the value is admittedly a crude estimate. A dependable figure may not be obtained until the assumptions of the first estimates have been tested over a period of years and appropriately revised. It has been widely recognized that the safe-yield value is a function of the assumptions made in the study and further that the value may change with changing cultural conditions on the surface of the basin. A common complaint about safe-yield definitions is that they are too vague. However, considering the variety of conditions a general definition must embrace, the vagueness can be justified. From the general definition, one will get almost no indication as to how safe yield in a particular basin should be computed. In each ground-water basin the specialists supervising the studies must "legislate" the assumptions and procedures. Especially in litigation, it is advisable to have advance agreement on the significant variables, among them:

1. In an area of cyclic rainfall, the base study period of representative rainfall;
2. The pattern of extractions;
3. The amount of water exported; and
4. The details of the hydrologic accounting methods.

Where surface cultural conditions are relatively stable, historic conditions may be considered representative of the near-term future. But on an area of rapidly changing culture it may be required to determine safe yield as of a single year or as of certain specified years. Then the computations are made in a hypothetical framework in which culture is fixed and the water crop is disposed of through a representative period assumed the same as the historic study period. The possibilities of checking the validity of such estimates are unfortunately limited.

In presenting the factors affecting safe yield, we might advantageously follow the outline of Todd as presented previously.

WATER SUPPLY AVAILABLE TO THE BASIN

It has been suggested as axiomatic that safe yield cannot exceed the long-time mean annual water supply to the basin. This concept bears re-examination. Whereas the general definition of safe yield may be vague, the test of whether safe yield has been exceeded is often more definitive. Safe yield has been most generally considered in terms of actual or potential extractions from a ground-water basin. If these extractions cause a progressive lowering of the water table, safe yield has been exceeded. If limited by economic, quality, or legal

factors, safe yield will be held to a lower value than in the instances where the ultimate limit, water supply is the controlling factor.

It is highly desirable, from a practical standpoint, to associate safe yield rigidly with pumpage (and with surface diversions, if these are involved). The determination of safe yield is usually not undertaken until there are some actual or imagined symptoms of overdraft. Quite often the determination is made in conjunction with litigation. At the end of the litigation or hearing, extractions may be curtailed, as in the classic Raymond Basin case. The only hydrologic item which can be apportioned effectively is pumpage. Consequently, safe-yield values expressed in terms other than pumpage may result in great confusion. For example, a common approach is to take inflows, subtract outflows and consumptive use, assume the difference is deep percolation, and call this safe yield. In this approach, deep percolation (not pumpage) is used as the measure of safe yield. Such an assumption may be incorrect. If water pumped from the basin is used on the surface of the basin, there may be an appreciable return to ground-water storage from the water applied. Safe yield (pumpage) then is larger than the average annual percolation of new water by the amount of the pumpage return. This phenomenon of re-circulation cannot be ignored if water-table trends are to be used as tests of safe-yield operation.

At the other extreme is the ground-water basin from which all the water pumped is exported. Under that circumstance there will be no local pumpage return and the safe yield might be quantitatively equivalent to the average annual percolation of new water. In many ground-water basins there is an intermediate situation, in which a part of the pumpage is used locally and a part is exported.

Computing safe yield in terms of "pumpage for consumptive use" may lead to confusion. If a man requires an estimated 1,000 acre-ft per yr to supply the consumptive use requirements of his crops, he may have to pump 2,000 acre-ft per yr. Decrees based on net pumpages or "pumpage less returns" are to be avoided, or the door will be left open to argument over irrigation efficiencies. In any event, it will be necessary to convert the net pumpages to gross pumpages to arrive at a workable apportionment.

With regard to water pumped and used locally, there is a question of salt balance, for obviously re-circulation is in the direction of a salt build-up. How much re-circulation can be permitted without seriously affecting salt balance is dependent on gross inflow-outflow relationships. Adverse salt balance makes itself felt only slowly, and it may be difficult to generate enough concern to start a program to reverse the trend. If decrees consider only pumpage and water tables, salt balance problems will tend to be ignored.

ECONOMIC FACTORS

It is probable that pumping in a few basins has been discouraged primarily by excessive lifts. However, there is some question whether economics, in any appreciable number of instances, functions as the primary limiting factor in safe yield. In most basins with large pumping lifts, the excessive lowering of water levels is associated with severe overdraft. That is, the economic factor did not begin to operate until long after the water-supply factor in safe yield had been exceeded.

There have been many suggestions that economics has nothing to do with safe yield, and there is much in favor of this point of view. In the definitions

of safe yield there is no indication that the water is intended for a specific use. Is the amount of water available decreased by the inability of someone to justify high pumping costs?

In heavily overdrafted basins, as water levels fall, there tends to be a gradual evolution of beneficial uses. In the early days of its development, a groundwater basin may have been occupied primarily by agricultural lands. As water levels are lowered the original crops may be replaced by crops bringing a higher return. With further lowering, more and more agricultural pumping is discontinued, and only industrial and domestic or municipal pumping remains. The transition often eases (but rarely stops) overdraft.

QUALITY FACTORS

In areas of sea-water intrusion the influence of water quality on safe yield is most obvious. Often the advance of the sea-water front is the result of general overdraft on an aquifer, which except for that overdraft, would be losing fresh water to the ocean. In coastal areas of cyclic rainfall, excessive losses by underflow to the ocean may occur during wet periods. To avoid these losses and maximize yield, it may be effective management to permit temporary sea-water intrusion during drought periods. In other areas the overdraft is not general and quality deterioration is related to local overpumping; outflow to the ocean continues from other portions of the aquifer.

It has been suggested that safe yield is exceeded if water levels are so lowered as to induce inflow of inferior waters. The mere fact of inflow of inferior waters is, of itself, not critical. More important is the concentration-volume factor and the effect of this inflow in the receiving waters. If dilution is adequate and well-water quality is not seriously deteriorated, there may be no reason for alarm.

Adverse salt balance is an insidious problem in many arid and semiarid basins. The salt build-up and attendant problems become evident much less quickly than those involving inssufficient replenishment or transmission capacity. Adverse salt balance is often difficult of proof. Even more difficult is convincing authorities to take appropriate action.

LEGAL FACTORS

There are at least two situations in ground-water basins where injunctions might be obtained by owners of water rights with the effect of preventing the development of full safe yield. This would occur in a basin with good recharge, which, if not intercepted, would waste to the ocean or to a closed desert basin. Developing the full safe yield may depend on substantial vertical cycling, artificial lowering of the water table during drought periods, followed by natural or artificial filling in succeeding wet periods. One problem is the fringe-area pumper. His wells are near the edge of the basin, and as water levels are lowered, production drops and the wells may go dry. But the assumed lowering of water levels during drought periods might have resulted in a substantial increase in safe yield. Granted an injunction, the fringe-area pumper could prevent optimum cycling, thus limiting the development of full safe yield.

An even more serious deterrent to effective ground-water management is the vested right to divert rising waters. It is hydrologically unsound to con-

sider rising waters as normal surface flow, and yet there is a common tendency to make no legal distinction between these. An owner of a vested right to rising ground waters vigorously asserting his claim might, for the sake of having available at the surface a relatively small flow, prevent the development of hundreds of times this amount as safe yield.

CONCLUSIONS

Although the concept of safe yield is a necessary one, the term "safe yield" should be replaced by "sustained yield" or "perennial yield." The computation should be made in terms of a potential draft on the ground-water basin rather than on some unmeasurable factor such as consumptive use. Usually safe yield is limited by the quantity of new water available. If there is a salt-balance problem, allowable draft may have to be decreased so that outflow may be increased. Although excessive pumping lifts have been cited as a potential limitation on safe yield, it is difficult to find instances where this has been true. More serious is the limitation certain legal rights may place on the development of full safe yield.

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DISCUSSION

ARTIFICIAL RECHARGE OF GROUND WATER RESERVOIRS OF CALIFORNIA[a]

Closure by Raymond C. Richter and Robert Y. D. Chun

RAYMOND C. RICHTER,[6] and ROBERT Y. D. CHUN,[7] M. ASCE.—It is agreed that there is a definite need for improved techniques to obtain and maintain high long-time infiltration rates. As Max Suter, F. ASCE is probably aware, there are many agencies currently engaged in studies to establish procedures for increasing the rate of placing water into ground water basins. The University of California, United States Soil Conservation Service, and the Texas High Plains Underground Water Conservation District are examples of agencies conducting studies of this type.

Suter lists some geological and hydrological factors that are important to any discussion of influences affecting infiltration rates. These and other factors have been presented in the paper.

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[a] December 1960, by Raymond C. Richter and Robert Y. D. Chun (Proc. Paper 2281).

[6] Superv. Engr. Geologist, Calif. Dept. of Water Resources, Sacramento, Calif.

[7] Assoc. Hydr. Engr., Calif. Dept. of Water Resources; Los Angeles, Calif.

METHODS OF APPLYING IRRIGATION WATER[a]

Closure by Paul H. Berg

PAUL H. BERG,[3] M. ASCE.—The writer used the comparison to illustrate the point that demand for irrigation water becomes more nearly simultaneous for all farms and all crops subsequent to periods of heavy rainfall occurring during the growing season. When such a condition is likely to occur each season, a demand system with capacity to meet such simultaneous requirements is desirable. The statement that a demand system dictates a much greater capacity than a rotation system is based on experience where irrigation outlet capacities are usually a minimum of 4 cfs for delivery to 100 acres or less. The sum of the outlet capacities is approximately two times the designed main canal capacity where the system is designed for demand operation. Systems requiring rotation operation are generally somewhat smaller, having a total outlet capacity about three to five times the main canal capacity. Most irrigators do not demand the full outlet capacity, even during periods of peak irrigation requirements.

The writer's statement concerning simultaneous demands for water by all farms and all crops following heavy rain indicates a greater probability of simultaneous demand than is shown in Efstratiadis' example.

The writer hoped that he would receive some comment concerning the permissible slope for irrigated fields in humid regions for various soil types.

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[a] September 1960, by Paul H. Berg (Proc. Paper 2595).

[3] Proj. Mgr., Kansas River Projects, Bur. of Reclam., Kans.

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LOS ANGELES WATER SUPPLY AND IRRIGATION[a]

Discussion by Harry F. Blaney

HARRY F. BLANEY,[8] F. ASCE.—The writer, a native of Los Angeles, Calif. is especially interested in Morris' excellent paper on the history and development of water supply for this city. The accomplishments of Morris, as Chief Engineer and General Manager of the Los Angeles Department of Water in improving the city system are outstanding.

Some historians[9] indicate that probably the first modern irrigation in the United States was started in Los Angeles and vicinity shortly after this pueblo was founded by the King of Spain in 1781. A small dam was built across Los Angeles River at the site of the old Buena Vista Street bridge. This was a communal undertaking. A ditch (Zanja Madra) was constructed from the dam to supply the pueblo with water for irrigation and for domestic use. Irrigated fields of wheat, maize, and vegetables lay along Alameda Street. The writer remembers as late as 1900 the zanja irrigation system extended along Figueroa Street as far south as the present University of Southern California campus.

Morris mentions that King Carlos III of Spain granted to the pueblo of Los Angeles all the waters of the Rio de la Porciuncula (Los Angeles River). Acording to Hutchins:[10]

> "In western water law, the pueblo water right is the paramount right of an American city as successor of a Spanish or Mexican pueblo to the use of water naturally occurring within the old pueblo limits to supply the needs of the city and its inhabitants. Although the Spaniards made settlements in many parts of the Southwest, the only states in which questions of pueblo water rights have yet been litigated are California and New Mexico.
>
> Inquiry into the origin of the pueblo rights doctrine begins in California where, as elsewhere in the Southwest, colonization by Spain included establishment of civil pueblos, religious missions, and military or presidial towns. In Spain, waters were held by pueblos as common property for domestic use, irrigation, and other purposes under administration of town officials. At the early agricultural pueblos of San Jose

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[a] December 1960, by Samuel B. Morris (Proc. Paper 2671).

[8] Irrig., Southwest Branch, Soil and Water Conservation Research Div., Agric. Research Service, U. S. Dept. of Agric., Los Angeles, Calif.

[9] "History of Los Angeles," by Charles D. Willard, Los Angeles, Calif., December, 1901.

[10] "Pueblo Water Rights in the West," by Wells A. Hutchins, <u>Texas Law Review</u>, Reprint, June, 1960.

and Los Angeles, California, irrigation was an all important consideration, and the American municipalities were confirmed in their rights and responsibilities as successors of the pueblos."

The author states that the approximate cost of water for irrigation in San Fernando Valley has been $7.00 per acre-ft. In a study[11] in 1930, the writer found that the annual cost of irrigation water (including district taxes and interest on retired bonds) to farmers in the Valley ranged from $8.85 per acre for deciduous trees to $19.55 per acre for alfalfa. The annual quantity of irrigation water delivered to the farms ranged from $1.19 to $1.87 acre ft per acre.

The author indicates that in 1925 there were 58,000 acres irrigated. However, this did not include double and inter-cropping acreage which amounted to approximately 12,000 acres making a total rotated irrigated acreage of 70,000 in 1925. As indicated by the author, the irrigated area had shrunk to about 15,000 acres in 1957-58. The areas formerly in irrigated crops are now (1961) occupied primarily by residences and industry.

11 "Cost of Irrigation Water in California," by Harry F. Blaney and Martin C. Huberty, State Bulletin No. 36, Div. of Water Resources, State of California, 1930.

METHOD FOR ESTIMATING CONSUMPTIVE USE OF WATER FOR AGRICULTURE[a]

Discussion by Harold D. Hafterson and Harry F. Blaney

HAROLD D. HAFTERSON,[17] F.ASCE.—Many methods for estimating consumptive use have been proposed since 1936. The discussions comparing the merits of the various methods have resulted in widespread use of the resultant data. Estimates of consumptive use have provided a basis for estimating water requirements in all regions of the United States and abroad. Considerable research has been carried on to measure more accurately the consumptive use for various common crops, with a view to refining the methods so that they can be applied in more detail. As indicated by the author, the estimates of consumptive use compare quite favorably. The general spread in annual, or even in monthly results rarely exceeds a few hundredths of a foot. As a matter of fact, the estimates generally agree much more closely than the independently measured results.

Therefore, the use of any one of the proposed methods will provide a reasonable base for estimates of water requirement or stream-flow depletion. Munson is to be commended for the development of a procedure which lends itself to such rapid determinations. It should provide a good and useful procedure for an expedient determination of average consumptive use for general crops.

The author developed a crop density factor of 1.77 for estimating an adjusted consumptive use figure for alfalfa. This was developed for Mesa, Ariz., and applied to estimates for crops at Davis, Calif. The results appear good. The application of this factor to distant areas seems to imply that it might also apply elsewhere.

The writer attempted to check this point by comparing results so determined with consumptive use measured on experimental tracts on the Deschutes Project in 1952 and 1953.[18] Factors of 1.12 and 1.32 were found for average measurements for alfalfa and ladino clover, respectively. This indicates that different values should be determined for this "density factor" for different localities or latitudes.

Certain items in the application of consumptive use data for estimating water requirements lead to the conclusion that more refinement in the estimates of consumptive use may not be warranted until other appurtenant data are further refined. These data include, among other things, effectiveness of

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[a] December 1960, by Wendell C. Munson (Proc. Paper 2672).

[17] Chf. Hydrology Branch, U. S. Bur. of Reclam., Region 1, Boise, Idaho.

[18] "Irrigation Efficiency, Consumptive Use, Certain Soil Characteristics of the North Unit Deschutes Irrigation Project, Oregon," by J. A. Currie, J. W. Wolfe, and L. R. Swarner, Miscellaneous Paper 72, Agric. Experiment Sta., Oregon State College, Corvallis, May, 1955.

precipitation, usable soil moisture, farm application efficiencies, and water table conditions.

Considerably less time and effort have been expended on research to determine the practical efficiencies with which the water can be applied. The practical efficiencies are those which are compatible with economics of irrigation; particularly as affected by cost of labor, value or availability of water, or the maintenance of safe subsurface water table levels where drainage is a problem. In areas where consumptive use may average about 2.0 ft per season, the farm efficiencies may vary from 70% down to 30%, or even lower. A 10% variation in the prospective farm application efficiency (which is well within the limits of agreement on this factor) might make a difference of from 0.5 ft to more than 1.5 ft in the estimates of farm delivery requirements. This range in estimated farm delivery, resulting from reasonable difference of opinion regarding farm application efficiency, makes the small differences in estimated consumptive use of small consequence.

Another factor which might greatly affect consumptive use by crops and, consequently, the estimated irrigation requirement, is the average water table condition on a project. In a Provisional Supplement[19] to SCS-TP96, observed monthly consumptive use of alfalfa growing in lysimeters with high water table at Reno, Nev. varied from 25.52 in. to 43.49 in. when water tables varied from 2 ft to 5 ft below the surface. Thus it appears that the estimates of average consumptive use should also be varied by judgement to reflect existing or anticipated water use practices. The variations resulting from average farm practices or inadequate drainage facilities might well affect the consumptive use far more than indicated by temperature data.

In view of these relatively indeterminate factors which must be evaluated and used in the application of consumptive use estimates as a basis for water erquirements, it appears that a simple easy-to-apply method of estimating consumptive use is not only desirable, but adequate. It is wasteful to spend much time and effort to determine one portion of the problem and merely assume values for larger factors used in the solution.

HARRY F. BLANEY,[20] F. ASCE.—The data presented by Munson in developing another method of estimating consumptive use of water are a valuable addition to the literature of this important subject. The author's estimates of water consumption for irrigation projects by the Precipitation-Evaporation (P.E.) Index Method, are remarkably close to those made by the Thornthwaite, Lowry-Johnson, Penman and Blaney-Criddle methods. However, it is questionable whether the method is as simple as some of the other methods for estimating consumptive use for individual crops or for calculating consumptive water requirements for a farm growing several different crops. Also, there is a question of whether the method can be adapted to areas like southern California, where only a trace of precipitation occurs during the principal irrigation season, May to September, or in the arid Imperial Valley, California, where the mean annual rainfall is only approximately 3 in.

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19 "Monthly Consumptive Use by Irrigated Crops in Western United States," by Harry F. Blaney, Howard R. Haise, and Marvin E. Jansen, Provisional Supplement to SCS-TP-96, SCS., U. S. Dept. of Agric., Washington, D. C.

20 Irrig Engr., S. W. Branch, Soil and Water Conservation Research Div., Agric. Research Service, U. S. Dept. Agric., Los Angeles, Calif.

The monthly consumptive use for the crops, calculated by Halkias[21] using the Blaney-Criddle method as shown in Table 6, is not accurate. The writer's closure[22] to his paper on monthly consumptive use[23] called attention to the fact that Halkias used seasonal coefficients (K) instead of monthly values of (k) in the Blaney-Criddle formula u = k f. Table 9 gives the correct computations, which compare more favorably with the P.E. Index values shown in Table 6.

TABLE 9.—MEAN MONTHLY CONSUMPTIVE USE BY CROPS AS MEASURED AND COMPUTED BY THE BLANEY-CRIDDLE AND P.E. INDEX METHODS, AT DAVIS, CALIF.

Months	Measured Consumptive Use	Blaney-Criddle Method			P.E. Index Method Consumptive Use
		Method		Consumptive Use	
		(f)	(k)[a]		
	Inches			Inches	Inches
(a) Sugar Beets					
May	5.1	6.29	0.80	5.0	5.3
June	5.7	7.08	.80	5.7	6.2
July	7.1	7.63	.95	7.2	7.1
August	5.8	7.11	.80	5.7	6.6
Total	23.7			23.6	25.2
(b) Alfalfa					
May	6.8	6.50	0.80	5.2	6.4
June	7.9	7.07	.90	5.8	7.6
July	8.3	7.60	1.10	8.4	8.6
August	7.1	8.93	1.00	6.9	8.1
September	4.3	5.90	.80	4.7	5.8
Total	34.4			31.0	36.5
(c) Cotton					
June	7.0	7.21	0.95	6.9	4.9
July	7.4	7.41	1.00	7.4	5.6
August	6.0	6.83	.90	6.1	5.3
September	5.0	6.14	.80	4.9	3.8
Total	25.4			25.3	19.6

[a] Monthly use coefficients in Blaney-Criddle Method u = k f = consumptive use, inches in which $f = \frac{t\,p}{100}$, t = mean monthly temperature F° and p = monthly percentage daytime hours.[22,23]

Tables 5 and 6 indicate that adjustments must be made in the P. E. Method when the consumptive use for individual crops is computed. However, Munson has developed an ingenious method for estimating consumptive use for potential irrigation projects.

21 "Determining Water Needs for Crops from Climatic Data," by N. A. Halkias, F. J. Veihmeyer, and A. H. Hendrickson, Hilgardia, Vol. 24, No. 9, December, 1955.

22 "Monthly Consumptive Use Requirements of Irrigated Crops," by Harry F. Blaney, Proceedings, ASCE, Vol. 86, No. IR 2, June, 1960.

23 "Monthly Consumptive Use Requirements for Irrigated Crops," by Harry F. Blaney, Proceedings, ASCE, Vol. 85, No. IR 1, March, 1959.

HUMID ZONE IRRIGATION IN CEYLON[a]

Discussion by M. M. Ismail

M. M. ISMAIL.[2] —Dickinson's emphasis on the need for proper drainage to paddy fields is welcome. Ancient Ceylon had done well in developing the art of rice culture through methodical layout of benched fields, irrigation canals, and storage reservoirs. What was humanly possible within the capacity of manual and animal labor had been achieved. The statement that "irrigation agriculture declined largely as a result of repeated invasions from the Continent by raiders who used elephants to break holes in the earth dams" is open to doubt. Raiders from the Continent could not have crossed over with trained elephants. Ceylon had large herds of wild elephants, who are known to be a source of damage to crops and irrigation works. Judging from the recent painful experiences of floods in 1959, 1944, and droughts in 1934-35 and the malaria epidemic of 1934-35, it seems more reasonable to conclude that the decline of irrigation agriculture was due to the three major natural causes of flood, drought, and epidemics. Medical service had brought epidemics under control. Flood and drought are matters for the irrigation engineer.

Obviously multi-purpose River Valley projects are the answer to mitigate the extremes of floods and drought. Equally important is the necessity to bring about appreciable increase in the yield by better drainage, tillage, and fertilization. However, there are certain limitations to the achievement of these objectives in some river valleys of Ceylon, while others offer ideal condition for intensive land development for high yield in agricultural and industrial ventures. The southwest wet zone of Ceylon including the rich tea, rubber, and coconut growing areas enjoys equatorial rains in two spells of wet weather every month. The flood plains of the rivers in this part of the island such as Keleni Ganga, Kalu Ganga, Nilwala Ganga have rice fields which depend more on direct rainfall. Diversion structures on the tributaries to the rivers and minor field channels off them give a helping hand. But they are of no avail if rain fails and the tributary streams do not bring water. The elimination of floods in these river valleys is a problem which eludes economic solution. Partial flood-absorbing reservoirs are possible but at the expense of submerging more prosperous developed land, highways, and railways. That would be like demolishing a house to put up a "Pandal." The configuration of the semi-hilly terrain lower down is not helpful to layout irrigation canal systems on economic lines. Electric power would be the only advantage from such reservoirs. Therefore any attempt to increase rice yield per acre should be directed towards soil conservation and fertilizing.

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a December 1960, by P. F. Dickinson (Proc. Paper 2682).

2 Superintending Engr., Gal Ora Valley, Ceylon.

On the other hand river valleys in the dry zone particularly in the South and East present a good field for multi-purpose river valley project. The success or the maximum value of these projects depends on the method of approach to the hydrographic problem. This part of Ceylon gets 45 in. to 55 in. of rains between October and February. Between March and September the range is 15 in. to 24 in. Sixty year maximum since 1900 had been 93 in. and 35 in. respectively. The corresponding seasonal run-off in the semi-hilly catchment areas of possible reservoirs is in the order of 60 in. and 7 in. maximum; a minimum of 6 in. and 1 in. while the average is 21 in. and 3.5 in. A multi-purpose or dual purpose project should aim at impounding at least 48 in. run-off in the reservoir. This will ensure the following advantages: (a) the complete detention of all possible floods; (b) elimination of flood damage in the flood plains; (c) carry over excess storage into the ensuing year; (d) aids layout of good drainage system and (e) two season crop and rotation of crops. There are nearly fifty sites suitable for this type of storage dam in the eleven river valleys of southeast Ceylon draining nearly 2,500 sq. mile of hilly terrain. The irrigable command is 2,000 sq. mile including Gal Oya Valley project. Walawe Ganga and her neighbors in the South have eight sites for total flood absorbing reservoirs in 800 sq. mile drainage area. A special feature of these possible reservoirs is their limited flood ratio between catchment area and flood level water spread, mostly ranging from 7:1 to 12:1. Whereas reservoirs in Continental rivers have a ratio of 200:1 or more and could never hope to have total flood absorption.

Almost all these river valleys have rice fields irrigated by the ancient diversion system making use of the network of flood streams. The ancient stick and earth dams on those streams are being replaced by masonry regulators with wooden stop logs since 1880 or thereabout. Many more are yet to be constructed preferably with radial gates for control of flood within bankful stage after the construction of total flood absorbing dams for multi-purpose or dual purpose. Such flood-affected fields are now (1961) in the habit of raising a three-month crop of rice between February and June. Nearly 50% of them could be reclaimed for a wet season four-month crop between October and March, so that these same areas could qualify for a second rotational crop between May and September in step with the new bench land which may acrue under the new distribution system on higher contours of the table land between two river valleys. In order to achieve such co-ordination of lands and crops under a mult-purpose or dual purpose project, any outstanding diversion structures in the river division or flood plains should be profitably completed before the new reservoirs begin to function. Failure to do so would result in worsening of drainage in the lower fields, apart from extra cost in construction under more water logged foundation.

This form of incorporation of old drainage streams for irrigation in the river division or flood plains may be considered an advantage in the matter of economic use of water. The drainage from the bench lands on the upper contours is being turned over for irrigation of fields lower down. This may be as much as 20% of the supply for rice crop higher up if the soil is loose. Assuming a repetition of 20% drainage, the ultimate waste is 4%. It would be unworkable and uneconomic to plan out a new distribution system in the flood plains or deltaic areas of humid Ceylon if the idealist were to say that drainage streams should not be obstructed for irrigation. In spite of such temporary obstruction of drainage streams, there are no complaints of lack of drain-

age at crucial periods in the deltaic areas above an elevation of 1 ft MSL. However the necessity for early construction of masonry structures for control of water cannot be over emphasized.

However there is the extreme case of poor drainage in the deltaic areas ranging in elevation between 1 ft MSL and 3 in. below sea level. The traditional practice is manual de-watering (with a wooden scoop suspended on a tripod) for sowing and harvesting. Watering the crop in such cases is by inundation. The area under this category is nearly 2 to 3% of irrigable land in a river valley. Under favorable conditions such lands in Gal Oya Valley used to give the maximum yield in the valley, to the extent of 80 bu to the acre. This area is likely to suffer loss through excessive inundation under a multipurpose project. Pumping is the remedy. The cost of this pumping under such circumstances should be a charge to the whole project and not to the private owner of the land who enjoyed maximum yield in pre-scheme days. During 15% of time in pre-scheme days, there used to be some amount of salinity on account of drought and high admixture of sea water by wave action over the sand bar at 6 ft MSL, whereas the high tide is only 2 ft above MSL. Under a multipurpose project the salinity would be automatically reduced, but the necessity for pump would be aggravated for lowering the water table to 9 in. below MSL.

It is the general feeling locally that some amount of over irrigation is helpful in a rice field in the process of mudding the field and for weed control. It would neither amount to waste of water if the excess drainage could be picked up and turned over to fields lower down. Such details should receive the close attention of the agronomist, for best results. Duty of water is highest in bench land of poor soil. It varies with the season and age of the crop. Three-month variety of rice needs 4 months overall period of irrigation and a 4-month paddy needs 5 months overall period of irrigation. The latter is the usual crop between October and February or November and March. The rainfall being 48 in. extra irrigation of 24 in. is ample. Rainfall exceeding 60 in. in this season is not conducive to best results. The dry season crop of rice is usually a 3-month variety. Under strict control of water the same 72 in. supply will ensure a good crop of 3-month rice.

There is poverty, ill health and ignorance in the peasant who is expected to be uplifted to do development of land under new projects. The peasant is making good progress. Tractors are replacing the water buffalo. The age of multi-purpose river valley projects for total flood absorption and intensive and comprehensive land development which began in Gal Oya Valley can go on for a 100 yr or more in view of the high rate of increase in population. The irrigation engineer will have to be earnestly busy meantime in investigating and planning comprehensive river valley projects and do up the preparatory work of constructing diversional and flood control structures in their flood plains and install pumps for dealing with salinity and poor drainage in the otherwise low level fields.

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1. "Flood Control and Maximum Utilization of Water Resources Around Gal Oya Valley," Proceedings, Inst. of Engrs., Ceylon, October, 1958.

2. "Weather and Flood Forecasting in Gal Oya Valley," Proceedings, Inst. of Engrs., Ceylon, October, 1959.

3. "Water Resources Development in River Valleys in Southeast Ceylon," Proceedings, Agenda Item 4 of E.C.A.F.E., Regional Tech. Conf., December, 1960, Colombo.

LEACHING REQUIREMENTS IN IRRIGATION[a]

Discussion by V. S. Aronovici and W. W. Donnan

V. S. ARONOVICI[2] AND W. W. DONNAN,[3] F. ASCE.—Raymond Hill, F. ASCE, has made a noteworthy contribution to the extent that he has called attention to the often neglected, but significant, parameter of water quality in irrigation. The quality of irrigation water must be a primary consideration in computing both irrigation water demands per unit area and drainage facility design.

The principle of maintaining a steady state salinity level within the soil profile irrigated with salinized waters was clearly demonstrated by L. A. Richards, United States Salinity Laboratory.[4] This principle was further developed by Ronald Reeve, drainage engineer, United States Salinity Laboratory.[5] They illustrate the proportional relationship between irrigation water quality and leaching requirement to maintain a steady state salt concentration within the soil profile.

Hill presents an equation for the leaching requirement which is essentially the same as that presented by the Richards and Reeve. They state

$$\text{Diw} = \frac{\text{ECdw}}{\text{ECdw} - \text{ECiw}} \text{Dew} \qquad (8)$$

in which ECdw is the electrical conductivity of the leachate; ECiw denotes the electrical conductivity of the irrigation water; Diw is the total irrigation water; and Dew represents the total evapotranspiration.

Hill suggests that the average of the salt concentration of the irrigation water and the water which percolates beyond the root zone is a realistic value to use as the concentration of the soil solution. Field and laboratory observations suggest that this is not necessarily true. It is not clear to the writers how the percolate concentration may be determined, because the percolate salt concentration is dependent on the quality of irrigation water and the quantity of leachate. Evapotranspiration removes moisture from the soil between irrigations, thereby concentrating the salinity of the soil solution. Capillary moisture movement tends to concentrate salts near the soil surface. Capillary movement upward into the root zone from a temporary or permanent

[a] March 1961, by Raymond A. Hill (Proc. Paper 2757).

[2] Soil Scientist and Branch Chf., USDA, Pomona, Calif.

[3] Soil Scientist and Branch Chf., USDA, Pomona, Calif.

[4] "Diagnosis and Improvement of Saline and Alkali Soils," Agric. Handbook No. 60, U. S. Dept. of Agric., February, 1954.

[5] "The Relation of Salinity to Irrigation and Drainage Requirements," Third Internatl. Congress on Irrig. and Drainage.

saturation zone may further salinize the soil solution between irrigations. Consequently, it would appear that Hill's leaching requirement is not based on a reasonable assumption.

Although much is still to be learned of the relationship of plant tolerance to concentrations of salt in the soil solution during periods of evapotranspiration, the United States Salinity Laboratory justifiably makes the assumption that the concentration of the leachate, or that water which moves down beyond the root zone, cannot exceed the tolerance of a given crop. Thus the leaching requirement will depend on three basic factors: (1) The tolerance of a given crop to salinity of the soil solutions; (2) the concentration of salts in the irrigation water, and (3) evapotranspiration or water use by the crop.

Eq. 8 may be adjusted to compute directly the leaching requirement Ddw as

$$\mathrm{Ddw} = \frac{\mathrm{ECiw}}{\mathrm{ECdw} - \mathrm{ECiw}} \mathrm{Dew} \qquad (9)$$

The significance of this more realistic concept can be demonstrated by solving Eq. 9 to obtain the leaching requirement for a crop of low salt tolerance and a crop of moderate tolerance. For example, if the salt concentration of the leachate is used as a controlling factor, citrus has a tolerance of approximately 3.0 EC x 10^3 whereas potatoes are tolerant to about 5.0 EC x 10^3. Assuming a 30-in. and 20 in. evapotranspiration for the respective crops, the leaching requirement for citrus is 15 in. whereas that for the potato crop is only 5 in.

For sound salinity control through intermittent leaching, one must consider the nature and depth of the soil profile, monthly or annual effective rainfall which may contribute to leaching, and the drainage potential of the soil and substrata. Thus, no single variable such as irrigation water quality can be isolated from the final objective, which is to provide sustained maximum productivity under given environmental conditions.

WATER BALANCE RECORDER[a]

Discussion by Lloyd L. Harrold

LLOYD L. HARROLD,[10] F. ASCE.—The sensitivity and simplicity of a water balance recorder having such small border effects are highly desirable. It is likely that it will be used to supply much needed data on consumptive use of water where rooting depth of the crops is shallow.

Specific questions directed to the authors pertain to (1) the possibility or desirability of introducing tension to the soil at the bottom of the inner tank to prevent unnatural moisture accumulations at this point, and (2) how runoff and percolation are to be handled.

If investigations were conducted with soil in contact with ground water, water could be added or withdrawn from the lysimeter through the pipe, thereby maintaining a rather uniform water table depth.

The quantity of water added during periods of no rainfall would be equal to the quantity of evapotranspiration recorded on the chart and could be checked against the weight records. The quantity withdrawn during rainy periods could also be checked against the raingage totals and weight changes.

Is there a possibility that in the case of investigations without contact with a water table, there might be a greater accumulation of soil moisture in the soil layer above the gravel bed? There would be no tension at this depth to remove moisture from the soil pores in the lysimeter, a condition somewhat different than might be found in the surrounding fields when the soil depth was 200 cm or more. If this were the case, there could be more moisture available to plant roots in the lysimeters than to those in the adjacent fields. For bare soil evaporation, there would be little or no difference between lysimeter soil evaporation and field soil evaporation, as the moisture at a 100-cm depth probably has no effect on surface moisture available for evaporation.

There is no provision for surface runoff. Is it likely that you do not expect surface runoff to occur from rainfall on this soil of zero slope, either on the lysimeter or in the adjacent field?

The writer was grateful to note the world-wide references to current literature on lysimetry.

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[a] March 1961, by Hans C. Aslyng and Knud J. Kristensen (Proc. Paper 2762).

[10] Hydr. Engr., Research, Soil and Water Conservation Research Div., Agric. Research Service, U. S. Dept. of Agric., Coshocton, Ohio.

RELATION OF INTAKE RATE TO LENGTH OF RUN IN SURFACE IRRIGATION[a]

Discussion by Lyman S. Willardson

LYMAN S. WILLARDSON,[8] A. M. ASCE.—Bishop's suggested method provides a direct means of evaluating deep percolation losses. This now makes it possible to put deep percolation in its proper perspective with relation to labor and water savings. The analysis developed by the author should help to improve materially the efficiency of furrow irrigation systems.

A question arises with regard to two of the assumptions made by Bishop: (1) the triangular pattern of deep percolation loss and (2) the linear relationship between percolation losses and "n." Between Eqs. 7 and 8 in the text, the author states, "As t increases the intake rate approaches a constant value that will result in a triangular pattern for the deep percolation loss below the root zone as shown in Fig. 1." Fig. 1 shows the case where water is on the bottom of the field for four-time periods equal to the advance time. The deep percolation losses for short-time periods and for R values greater and less than four are not illustrated. Between Eqs. 10 and 11 Bishop assumes that the percolation losses have a straight line relationship for different values of "n."

Data from an actual field advance curve are used as a basis of comparison with the analytical results presented by Bishop. The curve is for a 47 gpm stream in a large furrow on a 0.34 slope. The infiltration data were assumed to get the necessary range of "n" values. Fig. 1 shows the advance curve used.

The shape of the advance curve at 40 min and 400 min was used to correspond to a rapid and a slow advance and R values of 0.5, 1, 2, 4, and 8 serve as examples. Values of (n+1) used were 0.3, 0.5, and 0.7 with a constant characteristic in the infiltration equation of 0.5. Fig. 4 shows the advance situations used for advance times of 40 min and 400 min. Also shown are the infiltration equations.

An example of the procedure is computed for illustrative purposes for the condition in which R equals 4 and (n+1) equals 0.5. In 40 min the water advances 367 ft. In which R is 4, the water remains on the lower end of the field for 160 min. It will then have been on the upper end of the field for 200 min. According to Eq. 1

$$d = \frac{Kt^{n+1}}{60(n+1)} = 0.5t^{0.5} \qquad (12)$$

the depth of water absorbed on the upper end would be 7.06 in. On the lower end, 6.33 in. would have been absorbed. Using the advance curve, the contact time for water at any point in the furrow can be determined. Dividing all the

[a] March 1961, by A. Alvin Bishop (Proc. Paper 2769).

[8] Agric. Engr., Southwest Branch, Soil and Water Conservation Research Div., Agric. Research Service, U. S. Dept. of Agric., Logan, Utah.

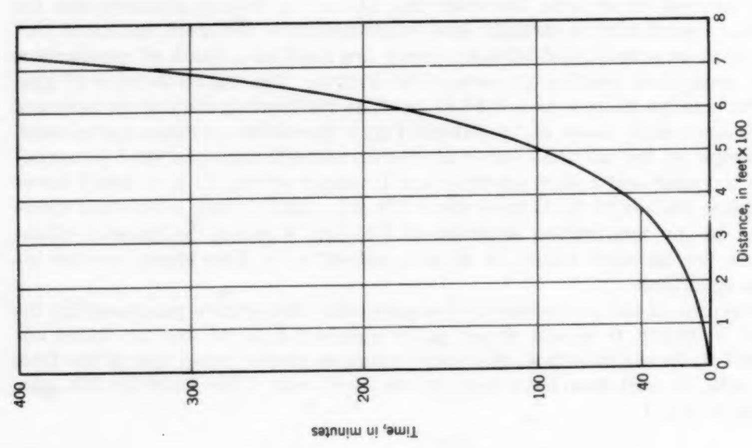

FIG. 3.—ADVANCE CURVE, MILFORD FURROW STUDY, FURROW 1, AUGUST 15, 1960

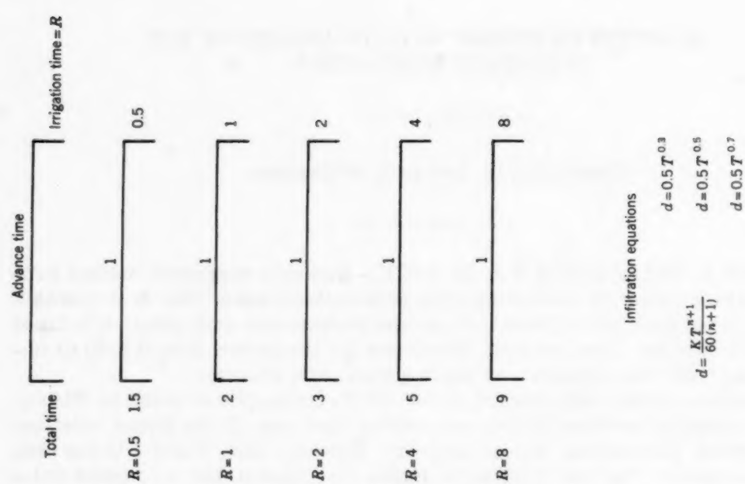

FIG. 4.—ADVANCE SITUATIONS, MILFORD FURROW STUDY, FURROW 1, AUGUST 15, 1960

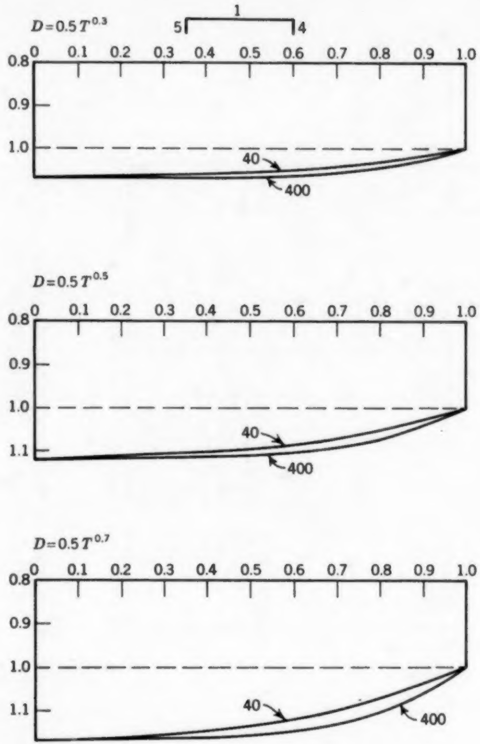

FIG. 5.—MILFORD FURROW STUDY, FURROW 1, AUGUST 15, 1960

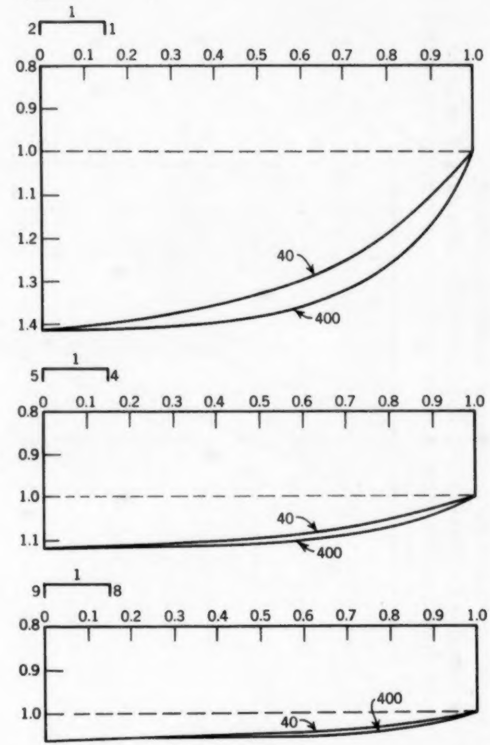

FIG. 6.—MILFORD FURROW STUDY, FURROW 1, AUGUST 15, 1960, D = 0.5 $T^{0.5}$

absorbed depths by 6.33 in. (the depth absorbed at the lower end of the field) and dividing each distance by 367 ft, the advance-penetration curves become dimensionless. Figs. 5 and 6 show the effects of infiltration and advance on water penetration. The areas of deep percolation were planimetered from these and similar curves to get the range of conditions desired.

Fig. 7 corresponds to Bishop's Fig. 2 and shows the loss curves as affected by advance and length of the irrigation period. For the condition of R equals

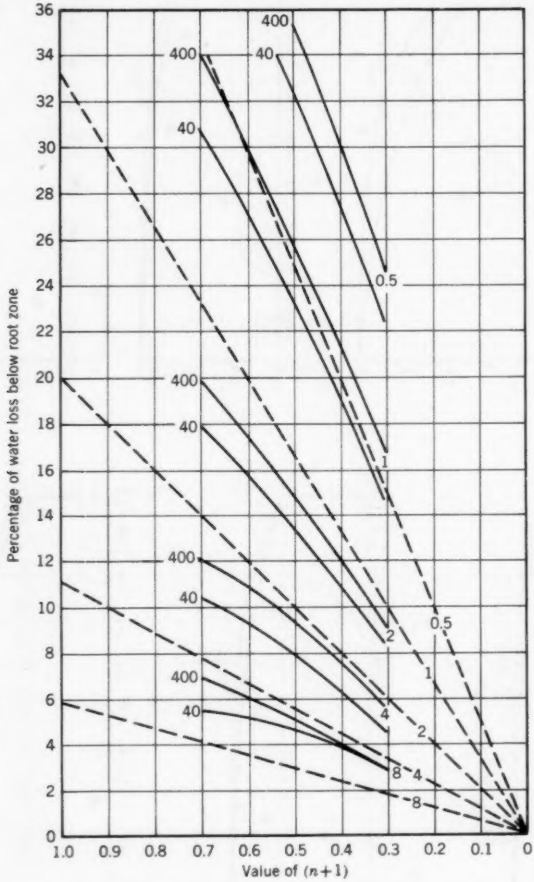

FIG. 7.—LOSS CURVES AS AFFECTED BY ADVANCE AND LENGTH OF IRRIGATION PERIOD

4 and (n+1) equals 0.5, consideration of the effect of advance and the non-triangularity of the deep percolation loss area results in an increase in the deep percolation from 5.6%, as suggested by Bishop, to 7.9% or 9.3%. Increasing the length of the irrigation period ten times from 40 min to 400 min does not cause as much error as the assumption of a triangular loss pattern. As can be seen from Fig. 7, decreasing the R value increases the differences.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 2703 is identified as 2703(ST1) which indicates that the paper is contained in the first issue of the Journal of the Structural Division during 1961.

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SEPTEMBER: 2588(IR3), 2589(IR3), 2590(WW3), 2591(IR3), 2592(HW3), 2593(IR3), 2594(IR3), 2595(IR3), 2596(HW3), 2597(WW3), 2598(IR3), 2599(WW3), 2600(WW3), 2601(WW3), 2602(WW3), 2603(WW3), 2604(HW3), 2605(SA5), 2606(WW3), 2607(SA5), 2608(ST9), 2609(SA5)[c], 2610(IR3), 2611(WW3)[c], 2612(ST9)[c], 2613(IR3)[c], 2614(HW3)[c].

OCTOBER: 2615(EM5), 2616(EM5), 2617(ST10), 2618(SM5), 2619(EM5), 2620(EM5), 2621(ST10), 2622(EM5), 2623(SM5), 2624(EM5), 2625(SM5), 2626(SM5), 2627(EM5), 2628(EM5), 2629(ST10), 2630(ST10), 2631(PO5)[c], 2632(EM5)[c], 2633(ST10), 2634(ST10), 2635(ST10)[c], 2636(SM5)[c].

NOVEMBER: 2637(ST11), 2638(ST11), 2639(CO3), 2640(ST11), 2641(SA6), 2642(WW4), 2643(ST11), 2644(HY9), 2645(ST11), 2646(HY9), 2647(WW4), 2648(WW4), 2649(WW4), 2650(ST11), 2651(CO3), 2652(HY9), 2653(HY9), 2654(ST11), 2655(HY9), 2656(HY9), 2657(SA6), 2658(WW4), 2659(WW4)[c], 2660(SA6), 2661(CO3), 2662(CO3), 2663(SA6), 2664(CO3)[c], 2665(HY9)[c], 2666(SA6)[c], 2667(ST11)[c].

DECEMBER: 2668(ST12), 2669(IR4), 2670(SM6), 2671(IR4), 2672(IR4), 2673(IR4), 2674(ST12), 2675(EM6), 2676(IR4), 2677(HW4), 2678(ST12), 2679(EM6), 2680(ST12), 2681(SM6), 2682(IR4), 2683(SM6), 2684(SM6), 2685(IR4), 2686(EM6), 2687(EM6), 2688(EM6), 2689(EM6), 2690(EM6), 2691(EM6)[c], 2692(ST12), 2693(ST12), 2694(HW4)[c], 2695(IR4)[c], 2696(SM6)[c], 2697(ST12)[c].

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JANUARY: 2698(PP1), 2699(PP1), 2700(HY1), 2701(SA1), 2702(SU1), 2703(ST1), 2704(ST1), 2705(SU1), 2706(HY1), 2707(HY1), 2708(HY1), 2709(PO1), 2710(HY1), 2711(HY1), 2712(ST1), 2713(HY1), 2714(PO1), 2715(ST1), 2716(HY1), 2717(SA1), 2718(SA1), 2719(SU1)[c], 2720(SA1)[c], 2721(ST1), 2722(PP1)[c], 2733(PO1)[c], 2724(HY1)[c], 2725(ST1)[c].

FEBRUARY: 2726(WW1), 2727(EM1), 2728(EM1), 2729(WW1), 2730(WW1), 2731(EM1), 2732(SM1), 2733(WW1), 2734(SM1), 2735(EM1), 2736(EM1), 2737(PL1), 2738(PL1), 2739(PL1), 2740(PL1), 2741(EM1), 2742(ST2), 2743(EM1), 2744(WW1), 2745(WW1), 2746(SM1), 2747(WW1), 2748(EM1), 2749(WW1), 2750(WW1)[c], 2751(EM1)[c], 2752(SM1)[c], 2753(PL1)[c], 2754(ST2)[c], 2755(PL1).

MARCH: 2756(HY2), 2757(IR1), 2758(AT1), 2759(CO1), 2760(HY2), 2761(IR1), 2762(IR1), 2763(HY2), 2764(ST3), 2765(HY2), 2766(HW1), 2767(SA2), 2768(CO1), 2769(IR1), 2770(HY2), 2771(SA2), 2772(HY2), 2773(CO1), 2774(AT1), 2775(IR1), 2776(HY2), 2777(HY2), 2778(SA2), 2779(ST3), 2780(HY2), 2781(HY2)[c], 2782(HW1)[c], 2783(SA2)[c], 2784(CO1), 2785(CO1)[c], 2786(IR1)[c], 2787(ST3)[c], 2788(AT1)[c], 2789(HW1).

APRIL: 2790(EM2), 2791(SM2), 2792(SM2), 2793(SM2), 2794(SM2), 2795(SM2), 2796(SM2), 2797(SM2), 2798(EM2), 2799(EM2), 2800(EM2), 2801(EM2), 2802(ST4), 2803(EM2)[c], 2804(SM2)[c], 2805(ST4)[c].

MAY: 2806(SA3), 2807(WW2), 2808(HY3), 2809(WW2), 2810(HY3), 2811(WW2), 2812(HY3), 2813(WW2), 2814(HY3), 2815(WW2), 2816(HY3), 2817(HY3), 2818(SA3), 2819(WW2), 2820(SA3), 2821(WW2), 2822(WW2)[c], 2823(HY3), 2824(SA3), 2825(HY3), 2826(SA3)[c], 2827(HY3)[c].

JUNE: 2828(SM3), 2829(EM3), 2830(EM3), 2831(IR2), 2832(SM3), 2833(HW2), 2834(IR2), 2835(EM3), 2836(IR2), 2837(IR2), 2838(SM3), 2839(SM3)[c], 2840(IR2)[c], 2841(HW2)[c], 2842(EM3)[c], 2843(ST5), 2844(ST5), 2845(ST5), 2846(ST5)[c].

JULY: 2847(PO2), 2848(SU2), 2849(HY4), 2850(PO2), 2851(HY4), 2852(PO2), 2853(SU2), 2854(HY4), 2855(PO2), 2856(PO2), 2857(PO2), 2858(SA4), 2859(SU2), 2860(SA4), 2861(PO2), 2862(SA4), 2863(HY4), 2864(HY4), 2865(HY4), 2866(HY4), 2867(HY4), 2868(PO2)[c], 2869(SA4)[c], 2870(SU2)[c], 2871(HY4), 2872(HY4)[c], 2873(SU2), 2874(SA4).

AUGUST: 2875(WW3), 2876(WW3), 2877(WW3), 2878(SM4), 2879(ST6), 2880(EM4), 2881(SM4), 2882(EM4), 2883(WW3), 2884(EM4), 2885(SM4), 2886(WW3), 2887(EM4), 2888(WW3), 2889(AT2), 2890(AT2), 2891(AT2), 2892(AT2), 2893(AT2), 2894(AT2), 2895(AT2), 2896(AT2), 2897(AT2), 2898(AT2), 2899(AT2), 2900(AT2), 2901(AT2), 2902(SM4), 2903(ST6), 2904(ST6), 2905(SM4), 2906(ST6), 2907(EM4), 2908(ST6), 2909(EM4), 2910(ST6), 2911(EM4), 2912(SM4), 2913(ST6), 2914(WW3)[c], 2915(ST6)[c], 2916(EM4)[c], 2917(SM4)[c].

SEPTEMBER: 2918(SA5)[c], 2919(HW3)[c], 2920(HY5)[c], 2921(SA5), 2922(PL2), 2923(IR3), 2924(HY5), 2925(HY5), 2926(CP1), 2927(HY5), 2928(IR3), 2929(IR3), 2930(HY5), 2931(CP1), 2932(PL2), 2933(HY5), 2934(HY5), 2935(HY5), 3936(HY5), 2937(HW3), 2938(CP1), 2939(PL2), 2940(SA5), 2941(SA5), 2942(SA5), 2943(HY5), 2944(PL2)[c], 2945(CP1)[c], 2946(IR3), 2947(HW3), 2948(IR3), 2949(IR3)[c].

c. Discussion of several papers, grouped by divisions.